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METHOD OF MOMENTS ANALYSIS OF SYMMETRIC DUAL REFLECTOR ANTENNAS WITH FEEDS

by

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Small symmetric dual reflector antennas have low efficiencies because of conflicting requirements for the subreflector and feed. Low efficiency is more pronounced for antenna configurations with main reflector diameters less than 50 times its operating wavelength. The subreflector and feed geometry must be small to reduce blockage but yet large enough to be an efficient scatterer. It may be possible to compensate for this by tuning the feed and subreflector. That is, by proper choice of the antenna geometry and dimensions and by using low-blockage feeds, the efficiency may be enhanced.

Existing computer codes have been modified in this thesis to reflect these changes in antenna feeds in order to optimize the antenna efficiency. A feed system consisting of a fed dipole in the presence of parasitic elements has resulted in an efficiency of 55%. Other untested feed configurations may produce even higher efficiencies.

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I. INTRODUCTION

A. ANTENNA DESCRIPTION

At high frequencies, an efficient method of focusing microwave energy into a desired directional beam is by the use of metallic reflecting surfaces. The reflector shape when using a single surface is usually parabolic, with a primary feed source located at the focus and directed onto the reflector area. Such a reflector may be a section of a surface formed by rotating a parabola about its axis. A single surface reflector however, does not allow both the aperture amplitude and phase distribution to be varied independently. The only means of control over the power distribution are by varying the focal length of the paraboloid or the feed pattern. Varying the focal length necessitates changing the physical dimensions of the antenna. Very large diameter front fed paraboloids are seldom used because of the long transmission line runs required to reach the feed. Adding a second reflecting surface, such as in the Cassegrain (parabola-hyperbola) or Gregorian (parabola-ellipse) design, leads to a more compact antenna than a single surface paraboloid of the same diameter. As discussed by Collin [Ref. 1], complete control over the aperture field distribution can be achieved by shaping both the subreflector and the main reflector.

As pointed out by Love [Ref. 2], reflector antennas are truly wideband devices, capable in principle of operation from radio to optical frequencies. Surface contours that are of particular interest at microwave frequencies are derived from the conic

sections. Conic sections include paraboloids, ellipsoids and hyperboloids. Axially symmetric reflectors are obtained by rotating these curves around the focal axis to generate a figure of revolution. Axially symmetric reflectors can suffer from severe blockage losses by the subreflector. To keep the subreflector blockage small requires a small subreflector size. Consequently, to simultaneously keep the blockage small, yet allow the subdish to be large enough so that it is an efficient scatterer restricts the main reflector diameter to be about 50 times the operating wavelength or greater. However, some recent applications such as direct broadcast satellites have been cause to re-examine the capabilities of reflector configurations less than 50 wavelengths, and perhaps as small as 20 wavelengths.

Another approach to designing efficient dual surface reflectors is to offset the surfaces to eliminate blocking. This would however, require more complex surface alignments as well as more restrictions on the feed. Such a design will also have degraded cross-polarization performance compared to a symmetric reflector.

B. CASSEGRAIN DUAL-REFLECTOR SYSTEM

The most common symmetric dual reflector configuration is the classical Cassegrain antenna shown in Figure (1). Based on the principles of geometrical optics, a spherical wave originating at the focus is transformed to a plane wave in the aperture plane. The feed is located at the accessible focal point and radiates the energy toward the subreflector which is in turn reflected toward

the main reflector. The internal focal point of the hyperboloid coincides with the focal point of the paraboloid.

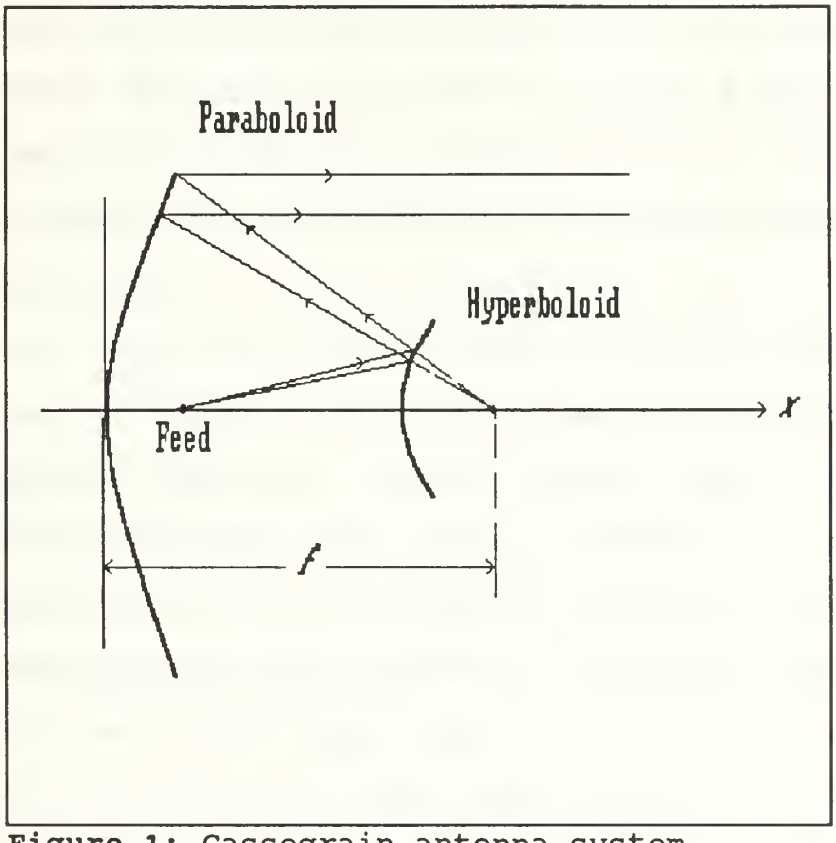

Figure 1: Cassegrain antenna system.

The effectiveness or efficiency of these antennas is a product of three factors. The first is the ability of the energy source to illuminate only the subreflector while minimizing the energy that radiates elsewhere. This is termed as "spillover efficiency." The second factor is the ability of the source to illuminate the parabola evenly, making maximum use of the entire reflector surface. Such is termed as "illumination efficiency." The third factor affecting efficiency is the blockage by the feed and

subreflector. The feed blocks rays from the subdish that would normally impinge on the main dish. Similarly, the subreflector blocks rays reflected from the paraboloid. In a classical Cassegrain system, the burden of optimizing these efficiencies is primarily placed upon the feed itself. The ideal feed would have a radiation pattern which would be uniform within the angle subtended by the subreflector and would fall abruptly to zero for all angles outside this region. Such a pattern is, of course not achievable in practice using feeds of limited extent [Ref. 3].

The blockage introduced by the subreflector as well as the interaction of the fields between the main reflector and the subreflector significantly affects the efficiency of the antenna. A suitable feed pattern coupled with the proper choice of the geometry and dimensions of the reflectors are required. Therefore, by proper tuning and by using low-blockage feeds, the antenna efficiency can be greatly improved.

C. SCOPE OF STUDY

The objective of this thesis is to optimize the performance (gain) of small, axially symmetric dual reflectors. A combination of the usual techniques such as shaping, low blockage feeds, and minimization of subreflector blocking and spillover are considered. In Chapter II, a study on shaping the reflectors in order to increase antenna efficiency is delineated. These techniques are based on geometrical optics principles and only give reliable results when the reflector dimensions are electrically large.

In chapter III, the scattered fields are obtained using the method of moments solution of the E-field integral equation (EFIE) for a perfectly conducting body of revolution. A computer program has been developed based on an existing code written by Mautz and Harrington that computes the electric surface current and far scattered field of a perfectly conducting body of revolution. The program was modified to incorporate the desired antenna feed configuration.

As stated earlier, most of the burden in maximizing the efficiency on Cassegrain antennas is placed upon the antenna feed itself. Chapter V discusses some of the comparisons and efficiency improvements derived from experimental feed reconfigurations. A systematic approach is taken for evaluating feed radiation patterns starting from a point feed to a dipole radiating in the presence of parasitic wires and rings. Figure (2) illustrates the most general feed configuration included in the main program. It is shown that the parasitic elements increase the feed directivity, and therefore reduce spillover loss. An efficient design was achieved by placing the fed dipole one quarter of a wavelength in front of the main reflector. This allows the cavity to be completely eliminated if the rim is replaced by a parasitic ring.

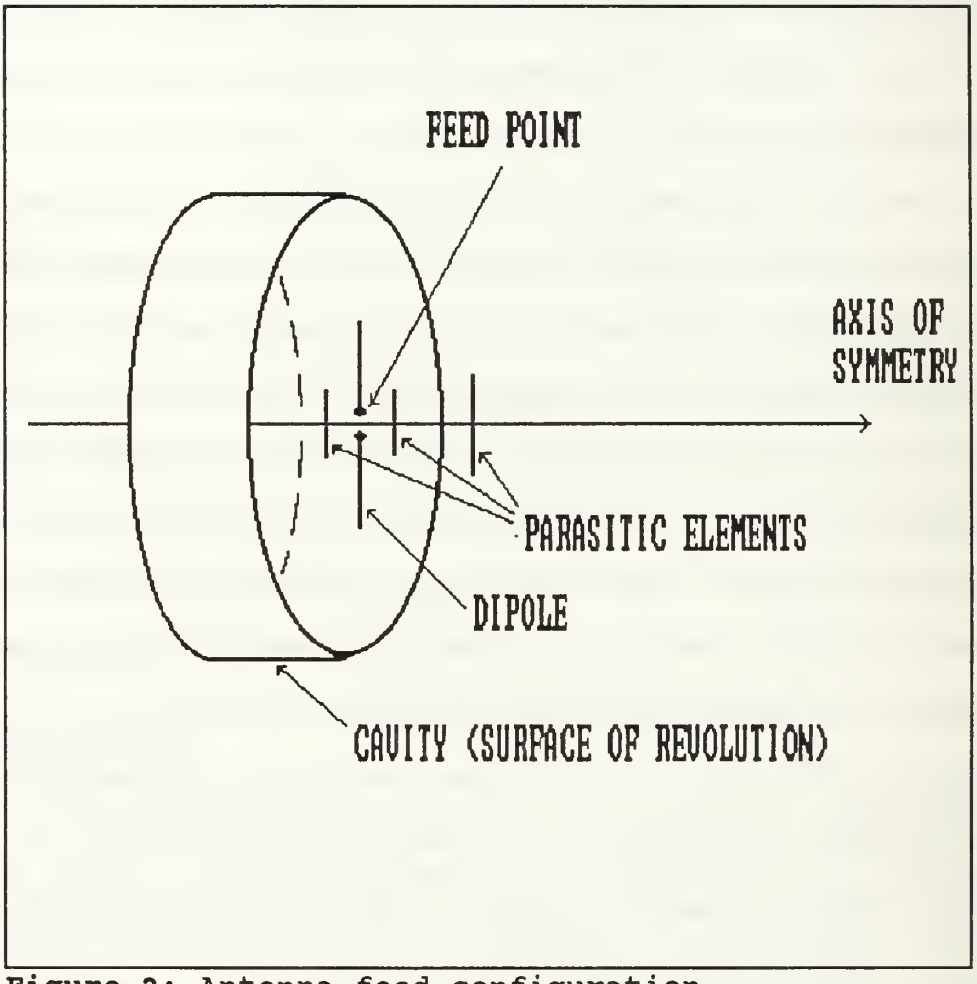

Figure 2: Antenna feed configuration.

II. ANTENNA OPTIMIZATION APPROACHES

A. DIRECTIVITY AND EFFICIENCY

Radiation from an antenna is not uniformly distributed in all directions. The directivity function $D(\theta,\phi)$ for the antenna describes the variation of the intensity with the direction in space. The directivity function is defined by Reference (1)

$$D(\theta,\phi) = \frac{\textit{power radiated per unit solid angle}}{\textit{average power radiated per unit solid angle}} = \frac{\partial P_r / \partial \Omega}{P_r / 4\pi} = 4\pi \frac{\partial P_r / \partial \Omega}{P_r} \tag{1}$$

where P_r is the total radiated power.

The gain of an antenna is similar to the directivity, except that the total power into the antenna rather than the total radiated power is used as the reference. As pointed out by Collin [Ref. 1], the relationship between gain and directivity is given by the efficiency, η

$$P_r = \eta P_{in} \tag{2}$$

where P_{in} is the total input power.

The directivity can be calculated by integrating the radiation pattern, which in turn can be determined by integrating the currents obtained from the method of moments (MM) solution of the

electric field integral equation (EFIE). Thus, the directivity, which is the maximum value of $D(\theta,\phi)$, is given by

$$D,\ \text{DIRECTIVITY} = 4\pi \frac{|E_{max}|^2}{\Omega_A} \tag{3}$$

where

$$\Omega_A = \int_0^{2\pi}\int_0^{\pi} |E(\theta,\phi)^2 R^2 \sin(\theta)\, d\theta\, d\phi \tag{4}$$

and $E(\theta,\phi)$ is the total radiated electric field. The maximum value of the electric field in the direction of the main beam is E_{max}.

B. FEED DESIGN REQUIREMENTS

In order to reduce spillover, the radiation from the feed must be highly directive; nearly all of the energy from the feed must be reflected by the subdish. For a cavity backed dipole feed to fulfill this requirement, it must have a prohibitively large diameter in order to produce a narrow beam. However, a large feed structure would then cause a substantial blockage of the energy from the subdish. This presents conflicting requirements necessary to maximize the antenna performance.

For small reflector systems, an efficient geometry is illustrated in Figure (3). The focus is located 0.25λ from the paraboloid, which serves as a ground plane for the dipole. This is a function normally performed by the bottom of the cavity. The cavity walls give the dipole a more directive pattern than it would have if it were isolated in free space. But this added directivity

mainly comes from the rim of the cavity, not the sidewalls. Therefore, the entire cavity can be eliminated if a parasitic ring is added to simulate the cavity rim. Dipoles are added on each side of the fed dipole to narrow the radiation pattern in the H-plane. A third parasitic dipole is located 0.25λ in front of the feed dipole to act as director.

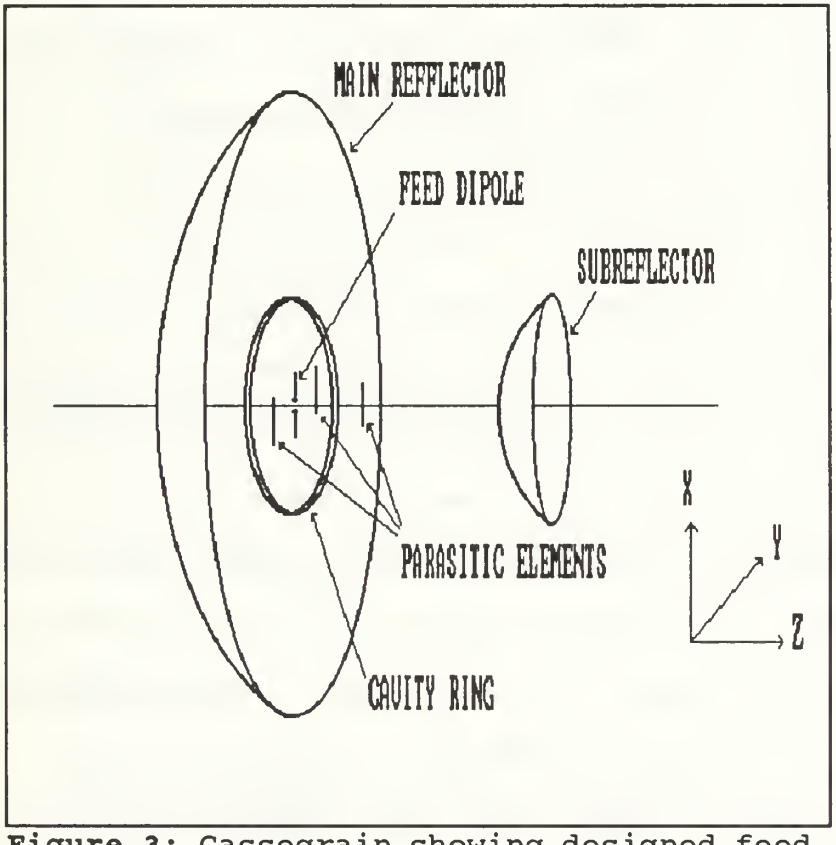

Figure 3: Cassegrain showing designed feed.

Thus, the three optimization objectives discussed in Chapter I are achieved. They are:

1. a low-blockage (low surface area) feed is employed
2. high feed directivity is achieved

3. the dimensions can be adjusted to fine-tune the efficiency of a small reflector.

C. SHAPING OF REFLECTORS

The primary objective of the feed design is to concentrate as much energy as possible toward the subreflector. In practice, the feed beam shape will have a smooth roll-off in gain at the subreflector edge, not an abrupt drop as desired. Also, the phase of the feed field will vary across the subreflector, whereas a constant phase is desired. These two shortcomings are a consequence of a high gain feed design.

Galindo [Ref. 4] has demonstrated that it is possible to compensate for the feed amplitude and phase error by modifying the shape of the reflector surface. To correct phase requires reshaping one of the reflector surfaces; to correct both amplitude and phase requires shaping both reflector surfaces. In this case, only the phase correction is considered, so the main reflector will be left unchanged.

The modification of a Cassegrain antenna system is shown in Figure (4). The power radiation pattern $F(\theta)$ has a feed phase center located as shown. For the present application, the path length $r+r'+r''$ must be chosen to compensate for the feed phase error at each angle θ, so that there would be no phase error in the reflected energy. This would result in the final illumination across the aperture $I(x)$ to have a uniform phase front.

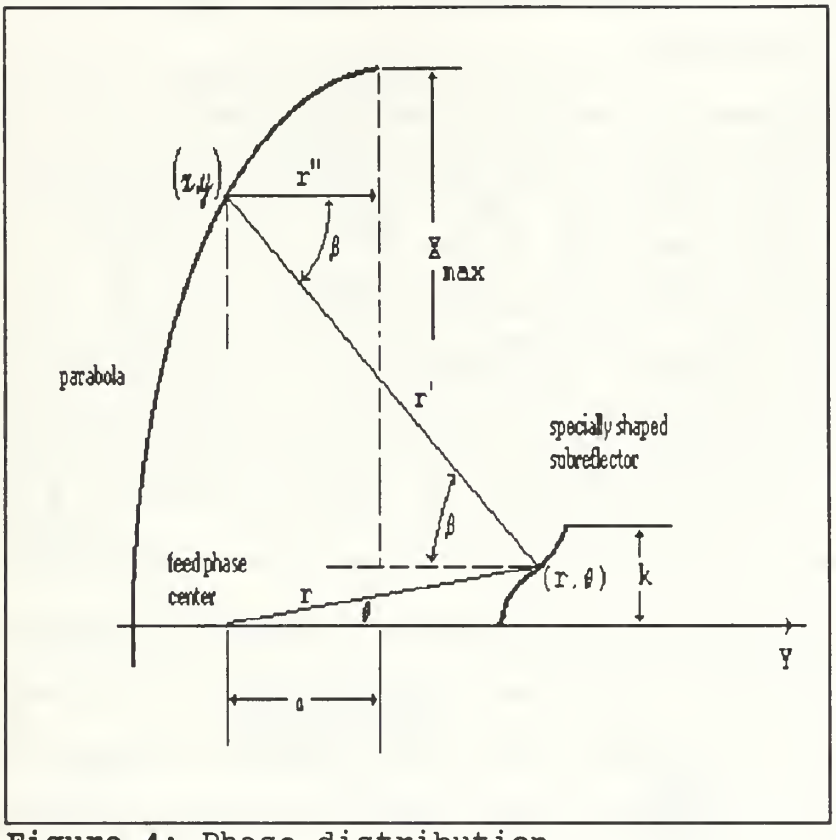

Figure 4: Phase distribution.

Keeping in mind that a constant phase front would be ideal, the required equation to obtain equal phase path lengths can be derived from geometry

$$k\left(r+y+\frac{x-r\sin\theta}{\sin\beta}\right)+\phi_f(\theta)=C\ (\text{constant}) \qquad (5)$$

where (x,y) and (r,θ) are the coordinates of the points on the main reflector and the subreflector and $\phi_f(\theta)$ is the feed phase in the direction of r. If ϕ_f were a constant, then Equation (5) would be satisfied by the standard Cassegrain system. When ϕ_f is not

constant over the angle subtended by the subreflector, (r,θ) must be chosen accordingly.

The contours of the corrected subreflector will depend on the feed phase error profile and the Cassegrain parameters. For a phase error that increases with θ, the shape can possibly resemble that shown in Figure (4). The new subreflector shape will cause more energy to be directed toward the main reflector edge which may or may not be a problem. If the resulting aperture illumination is not acceptable, it can be modified by changing the main reflector shape as described by Galindo [Ref. 4]. The effects of diffraction losses are not considered in this treatment since the analysis only used geometrical optics. The new surface shapes obtained using this method can be entered into the computer program discussed in Chapter IV to calculate the radiation pattern and gain of the antenna with shaped reflectors.

III. METHOD OF MOMENTS (MM)

A. ELECTRIC FIELD INTEGRAL EQUATION (EFIE)

In the following discussion, the phasor representations of the time-harmonic fields are used with the $e^{j\omega t}$ time dependence suppressed. It is also assumed that the conductors used in the computations are perfect electric conductors, thus, only electric currents will be present. In Figure (5), $\underline{E}_{inc}$ which is the incident field from the feed, induces a current $\underline{J}_s$ which radiates a scattered field $\underline{E}_s$.

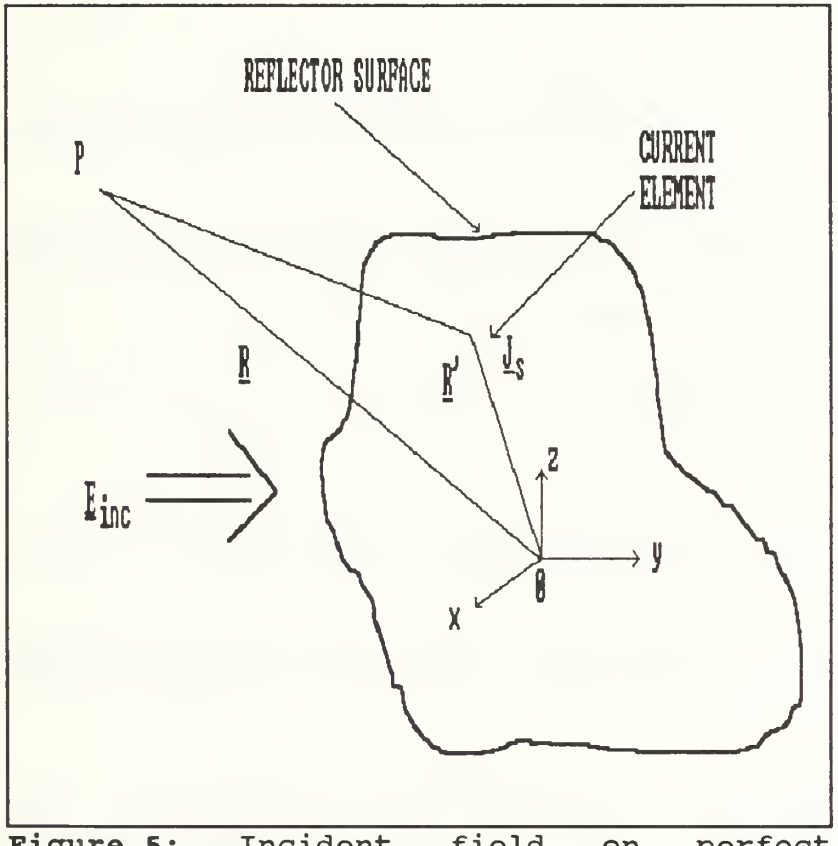

Figure 5: Incident field on perfect conductor.

The electric field due to the electric surface current on S is expressed as

$$E_s(P) = -j\omega A - \frac{j}{\omega\mu\varepsilon}\nabla(\nabla\cdot A) \tag{6}$$

where

$$A(P) = \frac{\mu}{4\pi}\int_S\int J_s(x',y',z')\,\frac{e^{-jkr}}{r}\,ds' \quad . \tag{7}$$

$\underline{A}$ is the magnetic vector potential as described by Mautz and Harrington [Ref. 5]. Denote the free space Green's function as

$$G(\underline{R},\underline{R}') = \frac{e^{-jkr}}{4\pi r} \tag{8}$$

where from Figure (5)

$$\begin{aligned} r &= |\underline{R}-\underline{R}'| \\ &= [(x-x')^2+(y-y')^2+(z-z')^2] \quad . \end{aligned} \tag{9}$$

Since the surface is a perfect conductor, the total tangential electric field on S must be zero

$$\begin{aligned} E_{inc}(P)\,|_{\tan} &= -E_s|_{\tan} \\ &= -[-j\omega A - \frac{j}{\omega\mu\varepsilon}\nabla(\nabla\cdot A)]\,|_{\tan} \end{aligned} \tag{10}$$

which leads to the general form of the EFIE

$$E_{inc}(P)\,|_{\tan} = \{j\omega\mu\int_S\int J_s\,G\,ds' + \frac{j}{\omega}\varepsilon\nabla[\nabla\cdot\int_S\int J_s\,G\,ds']\}\,|_{\tan} \quad . \tag{11}$$

The subscript tan is used to refer to tangential components of a vector. S includes all of the antenna surfaces, both feed and reflector. For long thin wires, the current will only have an axial

component and ∇ becomes $\partial\hat{t}/\partial t$, where t is the arclength along the wire. Furthermore, because the current is constant around the wire, $\int_s\int ds'$ reduces to $2\pi a\int_L dt'$ as shown in Figure (6). The requirement for the thin wire approximation to hold is that $a << \lambda$.

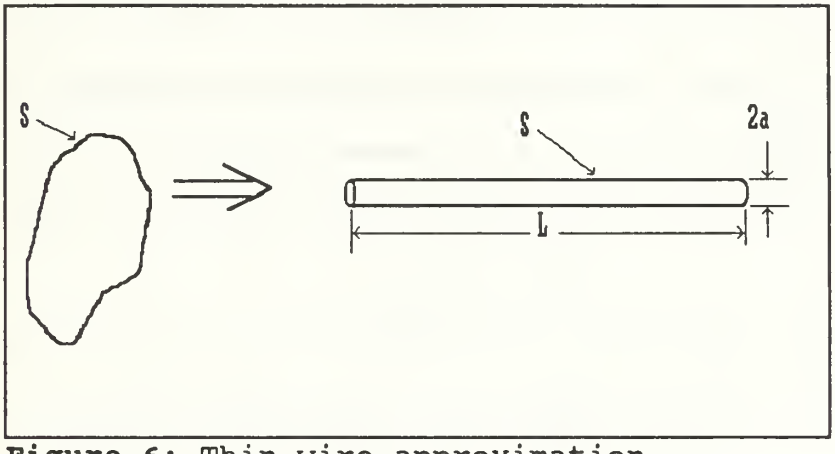

Figure 6: Thin wire approximation.

The unknown current $\underline{J}_s$ only depends on the primed quantities. G is a scalar that depends on both the primed and unprimed quantities. For convenience, define an operator $\mathcal{L}$ which will operate on $\underline{J}_s$

$$\mathcal{L}(\underline{J}_s) = j\omega\mu\int_s\int \underline{J}_s G\, ds' + \frac{j}{\omega\epsilon}\nabla[\nabla\cdot\int_s\int \underline{J}_s G\, ds'] \quad . \tag{12}$$

The last term in Equation (12) can be expressed as

$$\nabla\cdot\int_s\int \underline{J}_s G\, ds' = \int_s\int \nabla\cdot(\underline{J}_s G)\, ds' \tag{13}$$

by use of the vector identity

$$\nabla\cdot(\underline{J}_s G) = \nabla G\cdot\underline{J}_s + G(\nabla\cdot\underline{J}_s) \tag{14}$$

where ∇ operates on the unprimed coordinates (x,y,z). The gradient of G in terms of the two sets of coordinates are related by

$$\nabla G = -\left(jk+\frac{1}{r}\right)\frac{e^{-jkr}}{4\pi r}\hat{r} = -\nabla' G$$
$$\text{where}\ \nabla' = \frac{\partial}{\partial x'}\hat{x} + \frac{\partial}{\partial y'}\hat{y} + \frac{\partial}{\partial z'}\hat{z} \quad . \tag{15}$$

Using the surface divergence theorem developed by Mautz and Harrington [Ref. 5], it can be shown that

$$\int_s\int \nabla'\cdot(\underline{J}_s G)\ ds' = 0 \quad . \tag{16}$$

Finally, the integro-differential operator $\mathcal{L}$ can be written as

$$\mathcal{L}(\underline{J}_s) = \int_s\int \left[j\omega\mu\underline{J}_s G - \frac{j}{\omega\epsilon}\nabla\left[(\nabla'\cdot\underline{J}_s)\,G\right]\right] ds' \tag{17}$$

and the EFIE becomes

$$E_{inc}(P)\,|_{\tan} = \mathcal{L}(\underline{J}_s)\,|_{\tan} \quad . \tag{18}$$

B. SOLUTION OF EFIE USING METHOD OF MOMENTS

To solve the EFIE for a perfect electric conductor the MM is used. The current is expanded into a series with unknown coefficients

$$\underline{J}_s = \sum_{i=1}^{N} I_i \underline{J}_i \tag{19}$$

where I_i are the expansion coefficients and $\underline{J}_i$ are the basis or

expansion functions. From the linearity of $\mathcal{L}$, substitution of Equation (19) into Equation (18) yields

$$E_{inc}|_{tan} = \sum_{i=1}^{N} I_i \mathcal{L}(J_i) \quad . \tag{20}$$

Now, define a set of testing functions $\underline{W}_k$ and multiply each testing function times both sides of the EFIE and integrate. For Galerkin's method, the testing functions are chosen to be the complex conjugate of the expansion function (i.e., $\underline{W}_k = \underline{J}_k^*$). The testing procedure results in N equations which can be written as

$$V_k = \sum_{i=1}^{N} I_i Z_{ik} \tag{21}$$

for k = 1, 2, ... N, where N is the number of basis functions and

$$\begin{aligned} Z_{ik} &= \int\int_{S_k} ds \int\int_{S_i} ds' \left[j\omega\mu \underline{W}_k \cdot \underline{J}_i - \frac{j}{\omega\epsilon} (\nabla' \cdot \underline{J}_i)(\nabla \cdot \underline{W}_k) \right] G \\ V_k &= \int\int_{S_k} \underline{W}_k \cdot \underline{E}_{inc} ds \quad . \end{aligned} \tag{22}$$

Written explicitly, Equation (21) is

$$\begin{aligned} V_1 &= Z_{11} I_1 + Z_{12} I_2 + \ldots + Z_{1N} I_N \\ V_2 &= Z_{21} I_1 + Z_{22} I_2 + \ldots + Z_{2N} I_N \\ &\vdots \\ V_N &= Z_{N1} I_1 + Z_{N2} I_2 + \ldots + Z_{NN} I_N \end{aligned} \tag{23}$$

which in matrix notation becomes

$$[V] = [Z]\,[I] \quad . \tag{24}$$

To evaluate the impedance matrix, basis functions and testing functions must be defined. On the antenna surface, two orthogonal current components are required. They are the $\hat{t}$ and $\hat{\phi}$ components defined by Mautz and Harrington. On the wires, only a longitudinal component is needed if the thin wire approximation is used. The elements of Z are comprised of all possible combinations of basis and testing functions in Equation (22). Using the subscripts s and w to denote surface and wire, the impedance matrix will have the following block structure

$$\begin{bmatrix} Z_{-M}^{ss} & & & & & & & & Z_{-M}^{sw} \\ & \ddots & & & & & & & \vdots \\ & & \ddots & & & & & & \vdots \\ & & & \ddots & & & & & \vdots \\ & & & & Z_0^{ss} & & & & Z_0^{sw} \\ & & & & & \ddots & & & \vdots \\ & & & & & & \ddots & & \vdots \\ & & & & & & & \ddots & \vdots \\ & & & & & & & Z_M^{ss} & Z_M^{sw} \\ Z_{-M}^{ws} & \cdots & & & Z_0^{ws} & \cdots & & Z_M^{ws} & Z^{ww} \end{bmatrix} \begin{bmatrix} I_{-M}^{s} \\ \vdots \\ \vdots \\ \vdots \\ I_0^{s} \\ \vdots \\ \vdots \\ \vdots \\ I_M^{s} \\ I^{w} \end{bmatrix} = \begin{bmatrix} V_{-M}^{s} \\ \vdots \\ \vdots \\ \vdots \\ V_0^{s} \\ \vdots \\ \vdots \\ \vdots \\ V_M^{s} \\ V^{w} \end{bmatrix} \quad . \quad (25)$$

Although n can take on values between $\pm\infty$, it has been terminated at $\pm M$ in the above matrix. In practice, when the feed is on the reflector axis of symmetry, a converged solution can be obtained with M=1.

Each block on the diagonal can be decomposed further according to basis and testing components

$$\begin{bmatrix} Z_n^{tt} & Z_n^{t\phi} \\ Z_n^{\phi t} & Z_n^{\phi\phi} \end{bmatrix} \begin{bmatrix} I_n^t \\ I_n^\phi \end{bmatrix} = \begin{bmatrix} V_n^t \\ V_n^\phi \end{bmatrix} \qquad (26)$$

$$for\ n=0,\pm1,\pm2,\cdots,M$$

where the first subscript refers to the basis function and the second to the test function.

If the pattern is calculated for the antenna transmitting, the excitation vector will have only one nonzero value corresponding to the dipole feed point

$$\underline{V} = \begin{bmatrix} V_1 \\ \vdots \\ V_n \\ \vdots \\ V_N \end{bmatrix} = \begin{bmatrix} 0 \\ \vdots \\ 1e^{j0} \\ \vdots \\ 0 \end{bmatrix} . \qquad (27)$$

The unknown expansion coefficients are determined by solving the matrix in Equation (25) for [I]. To compute the electric field, the coefficients are used in Equation (19) which in turn is used in Equations (6) and (7).

C. MEASUREMENT MATRICES

The scattered field from the current $\underline{J}_s$ on the body can be determined using a measurement vector

$$R_m, \text{measurement} = \iint_S \underline{E}_r \cdot \underline{J}_m ds \tag{28}$$

where $\underline{E}_r$ is a unit radiated plane wave which is weighted by the current at that point on S.

For a θ polarized far field measurement

$$\begin{aligned} \underline{E}_r &= \hat{\theta} e^{-j\underline{k}\cdot\underline{r}} \\ &= \hat{\theta} e^{-jk[xu+yv+zw]} \end{aligned} \tag{29}$$

where u, v, and w are direction cosines defined as: $u = \sin\theta\cos\phi$, $v = \sin\theta\sin\phi$ and $w = \cos\theta$. Substitution of Equation (25) into (27) yields

$$R_m^{\theta} = \iint_S e^{-jk[xu+yv+zw]} (\hat{\theta} \cdot \underline{J}_m) ds' \quad . \tag{30}$$

The total electric field at the far-field point is the superposition of all surface current contributions

$$E_{\theta} = \frac{-jk\eta}{4\pi R} e^{-jkR} \sum_m R_m^{\theta} I_m \quad . \tag{31}$$

Similarly, for measuring the ϕ component

$$R_m^{\phi} = \iint_S e^{-jk[xu+yv+zw]} (\hat{\phi} \cdot \underline{J}_m) ds' \tag{32}$$

and the electric field would then be

$$E_{\phi} = \frac{-jk\eta}{4\pi R} e^{-jkR} \sum_m R_m^{\phi} I_m \quad . \tag{33}$$

IV. COMPUTER CODE DESCRIPTION

This chapter discusses the main program CASTRIDIP.F which is written in FORTRAN. The program utilizes the numerical solution covered in Chapter III. A listing of the computer code is included the Appendix. The antenna under consideration is a Cassegrain with a parabolic main dish and a hyperbolic subdish. The feed consists of a ring and three parasitic dipoles surrounding the fed dipole.

A. BRIEF DESCRIPTION OF THE MAIN PROGRAM

The program initially generates the sections of bodies of revolutions which includes the parabolic main reflector, the hyperbolic subreflector and the circular ring. The detached elements of the feed are then formulated. The subroutines ZMATSS, ZMATSW and ZMATWW compute the impedance matrix blocks. The impedance matrix is then assembled using the subroutines ZASMBO and ZASMBN. The matrix equation is solved using the subroutines DECOMP and SOLVE. The plane wave measurement vectors are calculated using PLANES and PLANEW. The scattered field is then obtained by performing the sums in Equations (31) and (33).

A flow chart derived from Reference (6) which illustrates the main program is shown in Figure (7). The input arguments which describe the geometry of the antenna feed is shown in Figure (8).

MAIN PROGRAM (CASTRIDIP.F)	SUBROUTINES
1. DEFINE GEOMETRY	
2. COMPUTE IMPEDANCE MATRIX BLOCKS	ZMATSS ZMATSW ZMATWW
3. ASSEMBLE IMPEDANCE MATRIX BLOCKS	ZASMBO ZASMBN
4. SOLVE MATRIX EQUATION	DECOMP SOLVE
5. COMPUTE PLANE WAVE MEASUREMENT VECTORS	PLANES PLANEW
6. OBTAIN THE SCATTERED FIELD	
7. COMPUTE TOTAL FIELD (FEED AND SCATTERED)	

Figure 7: Main program flow chart.

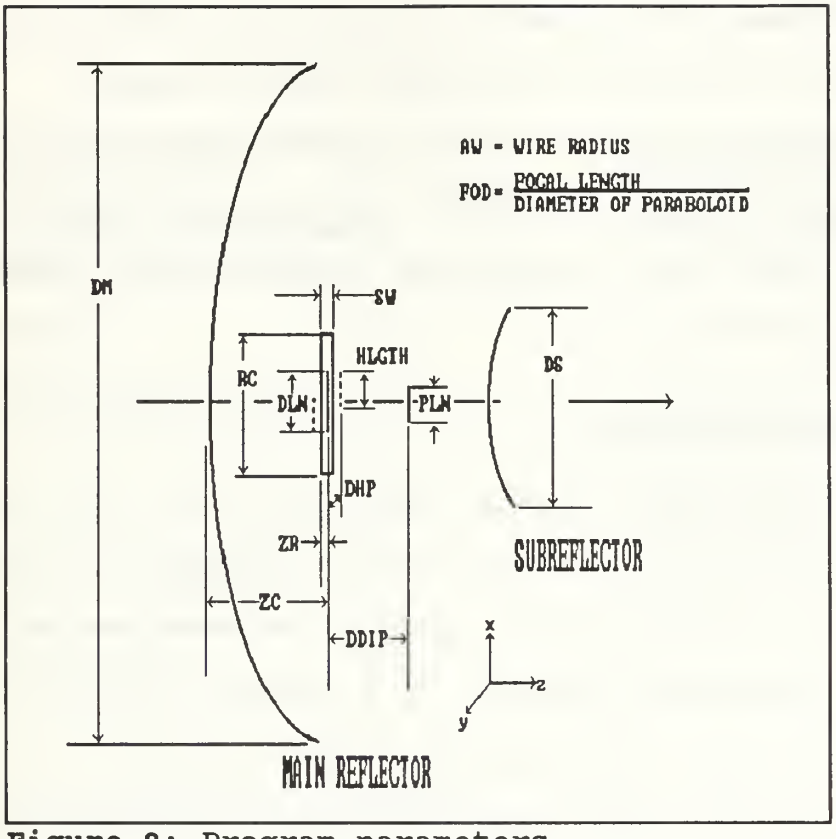

Figure 8: Program parameters.

The input parameters are:

DM = diameter of paraboloid (ground plane)

DS = diameter of subreflector (hyperboloid)

ZC = distance of dipole to ground plane

FOD = focal length to diameter ratio of the paraboloid

ZR = distance of ring from fed dipole along the z axis

RC = radius of ring

SW = ring width

DLN = fed dipole length

PLN = parasitic director dipole length

DDIP = distance between DLN and PLN along the z axis

AW = radius of dipoles

HLGTH = (2)parasitic (H plane) dipole length

DHP = H plane dipole distance from feed along the y axis

The main program implements the numerical solution described in Chapter III. All dimensions input to the program are in wavelengths.

1. GAIN CALCULATION

A separate computer code calculates the gain for the antenna configuration used in the main program. Far field pattern integration is employed using Gaussian quadrature. The previously calculated currents from the main program (saved on disk file PCURRENT) are used. From the gain, the efficiency of the antenna is computed using the gain of a uniformly illuminated aperture as a reference

$$\eta, \text{ efficiency} = \frac{G}{G_o} \tag{34}$$

where

$$G_o = \frac{4\pi A}{\lambda^2} \tag{35}$$

and

$$A = \pi\left(\frac{D_m}{2}\right)^2 \quad . \tag{36}$$

A flow chart for the gain program is shown in Figure (9).

GAIN PROGRAM (GAIN.F)	ASSOCIATED ARGUMENT
1. READ CURRENT COEFFICIENTS AND GEOMETRY	INPUT DATA FROM CASTRIDIP.F
2. COMPUTE SCATTERED FIELD	SUBROUTINES PLANE AND PLANEW
3. INTEGRATE TO GET GAIN	
4. COMPARE TO $4\pi A/\lambda^2$	

Figure 9: Gain program flow chart.

B. SUBROUTINES SOLVE AND DECOMP

The subroutines SOLVE and DECOMP are used to solve a system of N linear equations in N unknowns. The input to DECOMP consists of N and the N by N matrix of coefficients on the left-hand side of the matrix equation stored by columns in UL. IPS and UL are the outputs from DECOMP. These outputs are part of the input arguments to SOLVE. The rest of the input to SOLVE consists of N and the column of coefficients on the right-hand side of the matrix equation stored in B. The subroutine SOLVE puts the solution to the matrix equation in X. An in-depth explanation of SOLVE and DECOMP is enumerated by Mautz and Harrington [Ref. 7].

C. SUBROUTINES PLANES AND PLANEW

In order to calculate the elements of the plane wave receive vectors, the subroutines PLANES and PLANEW are used. R is the only output argument to these subroutines; the rest of the arguments are input arguments. These subroutines are described by Mautz and Harrington in [Ref. 8].

D. SUBROUTINES ZMATSS, ZMATSW AND ZMATWW

The blocks of the moment matrices in Equation (25) are calculated by the subroutines ZMAT, ZMATSW and ZMATWW and assembled. These matrices are stored in Z which is the only output argument of the subroutine. The rest of the arguments of ZMAT are inputs. The subroutine ZMAT is described by Mautz and Harrington [Ref. 8].

E. SUBROUTINES ZASMBO AND ZASMBN

The subroutine ZASMBO assembles mode independent blocks of Z. The subroutine ZASMBN assembles the mode dependent blocks in Z where the parameter NM is the mode number of the blocks ZSS and ZSW. Details of the subroutine can be found in Reference (8).

Listed in Table 1, as per Reference (6), is a summary of the subroutines in the program and the relevant quantities obtained.

TABLE 1: SUMMARY OF THE SUBROUTINES

GENERAL FUNCTION	SUBROUTINE NAME	QUANTITY CALCULATED
IMPEDANCE MATRIX BLOCKS	ZMATSS	$\underline{Z}^{tt}$, $\underline{Z}^{t\phi}$, $\underline{Z}^{\phi t}$, $\underline{Z}^{\phi\phi}$ (or Z^{ss} in Eqn. 25)
	ZMATSW	$\underline{Z}^{tw}$, $\underline{Z}^{\phi w}$ (or Z^{sw} in Eqn. 25)
	ZMATWW	$\underline{Z}^{ww}$
RECEIVE VECTORS	PLANES	$\underline{R}^{t\theta}$, $\underline{R}^{\phi\theta}$, $\underline{R}^{\phi\phi}$, $\underline{R}^{t\phi}$
	PLANEW	$\underline{R}^{w\theta}$, $\underline{R}^{w\phi}$
MATRIX OPERATIONS	DECOMP	DECOMPOSES $\underline{Z}$ MATRIX
	SOLVE	SOLVES DECOMPOSED $\underline{Z}$ MATRIX
	ZASMBO	ASSEMBLES MODE INDEPENDENT BLOCKS OF $\underline{Z}$ MATRIX (Z^{ww})
	ZASMBN	ASSEMBLES MODE DEPENDENT BLOCKS OF $\underline{Z}$ MATRIX (Z^{ss} and Z^{sw})

V. DATA ANALYSIS

A. FEED DESIGN STUDY

An antenna pattern with high directivity is essentially the goal of this thesis. With the feed configuration shown in Figure (2) and using a parabolic ground plane, several candidate configurations were examined. The two parasitic dipoles extending along the y axis of Figure (2) are referred to as the H-plane dipoles and the other parasitic dipole along the z axis as the E-plane dipole. Each of the parameters of the feed in Figure (2) was varied in small increments in order to observe the effect on the feed pattern.

A dipole above the paraboloid with a parasitic ring has the pattern shown in Figure (10). The solid line in the figure is the E-plane (ϕ=0°) pattern and the dashed line is the H-plane (ϕ=90°). The circular grid lines are in 5 dB increments and the angular grid lines in 15° increments. A typical subreflector will subtend roughly 60° (±30°). From the plot, it is evident that much of the feed energy will miss the subreflector.

If a parasitic element is added in front of the feed dipole and the ring is removed, the patterns shown in Figure (11) result. The parasitic dipole clearly illustrates the improvement in the directivity of the feed. A combination of a ring and a parasitic element resulted in a more directive and symmetric feed pattern as shown in Figure (12).

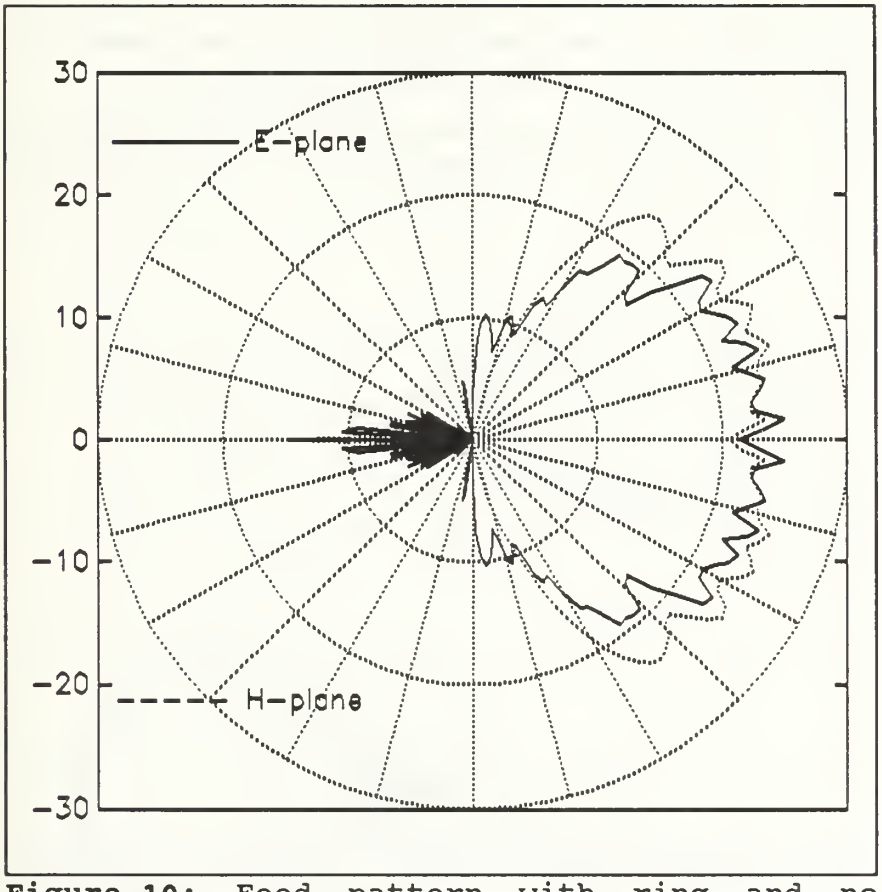

Figure 10: Feed pattern with ring and no parasitic dipoles.

The feed patterns shown in Figures (10) and (11) were run using the parameters shown in Table 2.

TABLE 2

COMMON PARAMETERS USED IN FIGURES (10) AND (11)

radius of ground plane	10λ
fed dipole distance from ground plane	0.25λ
ratio of focal length to diameter of ground plane	0.3λ

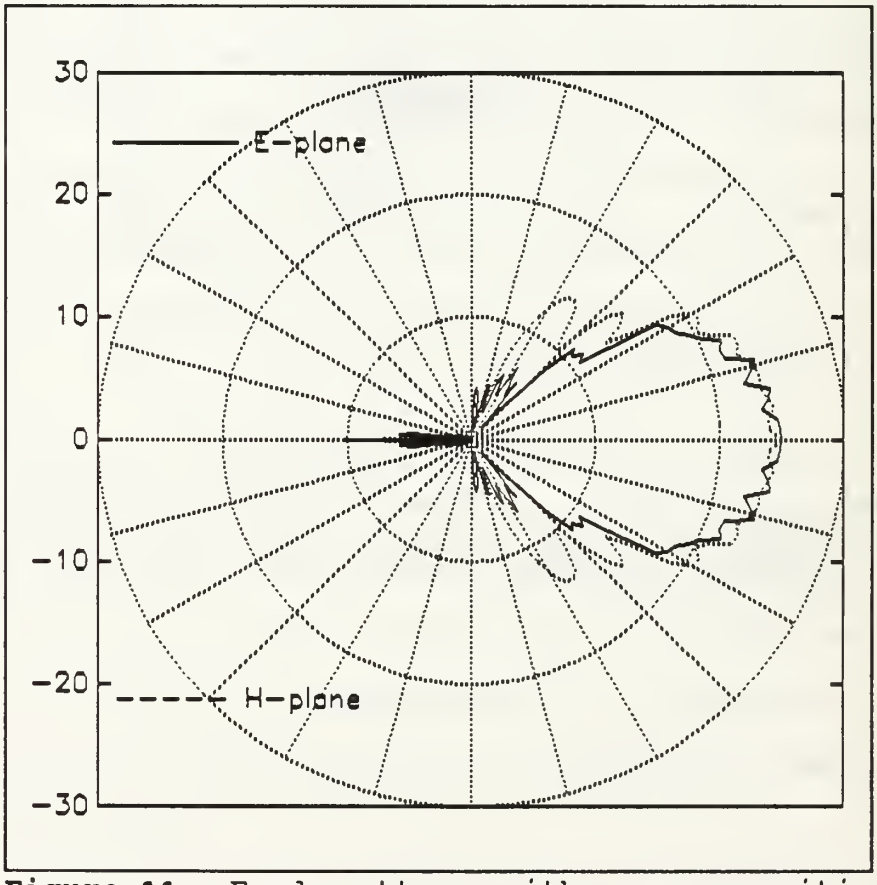

Figure 11: Feed pattern with one parasitic element in front of the fed dipole.

From Figure (8), it is obvious that there are many possible combinations of feed and reflector components. In an effort to find the optimum combination, each parameter was varied to examine its effect on gain while all other parameters were held constant.

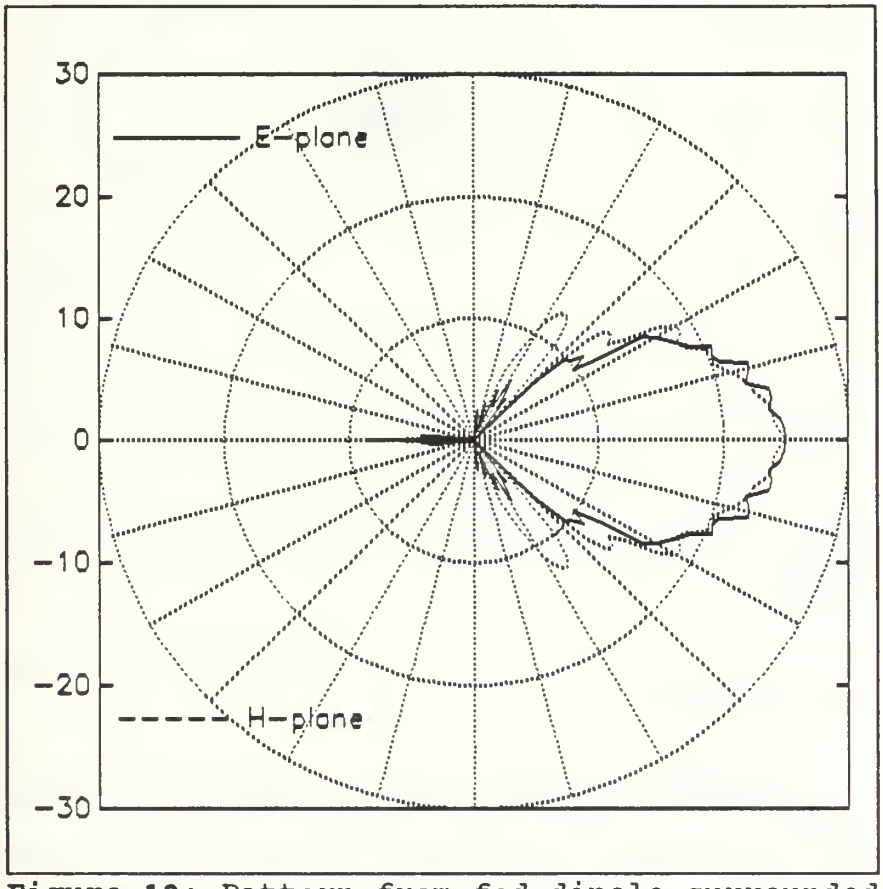

Figure 12: Pattern from fed dipole surrounded by ring and a parasitic director element.

The feed pattern of Figure (12) appeared to be the most directive of all the feed geometries examined. To reduce the H-plane sidelobes at 50°, the addition of two H-plane dipoles was investigated. The sidelobes were slightly lower as shown in Figure (13), however; the feed gain was not significantly higher.

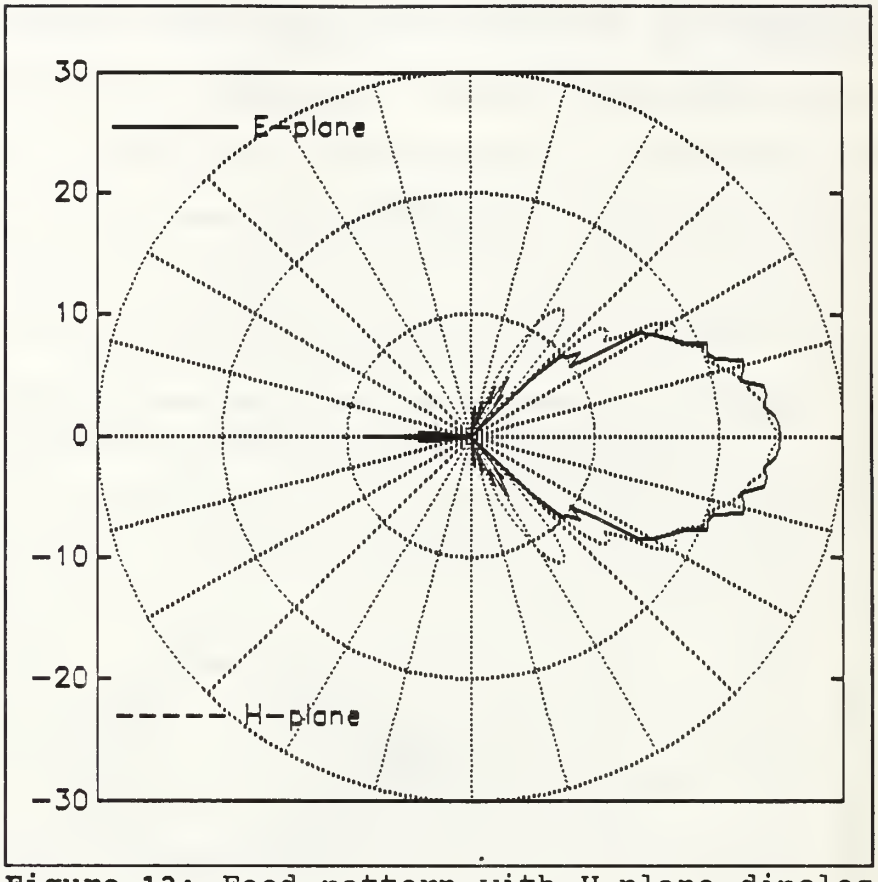

Figure 13: Feed pattern with H-plane dipoles added.

B. SHAPING INVESTIGATION

One approach to compensating for the feed phase error is to shape the subreflector as described in Section II.C. The phase of the radiation pattern in Figure (13) is plotted in Figure (14). It is essentially constant out to 40° except for a ripple which is primarily due to scattering from the rim of the main reflector. A 40° subreflector edge angle is about the maximum expected for antennas with FOD $\geq$ 0.3 and DS $\leq 7\lambda$. In light of this data, it is apparent that subreflector shaping does not offer any advantage. Therefore, shaping was not incorporated into the final antenna design.

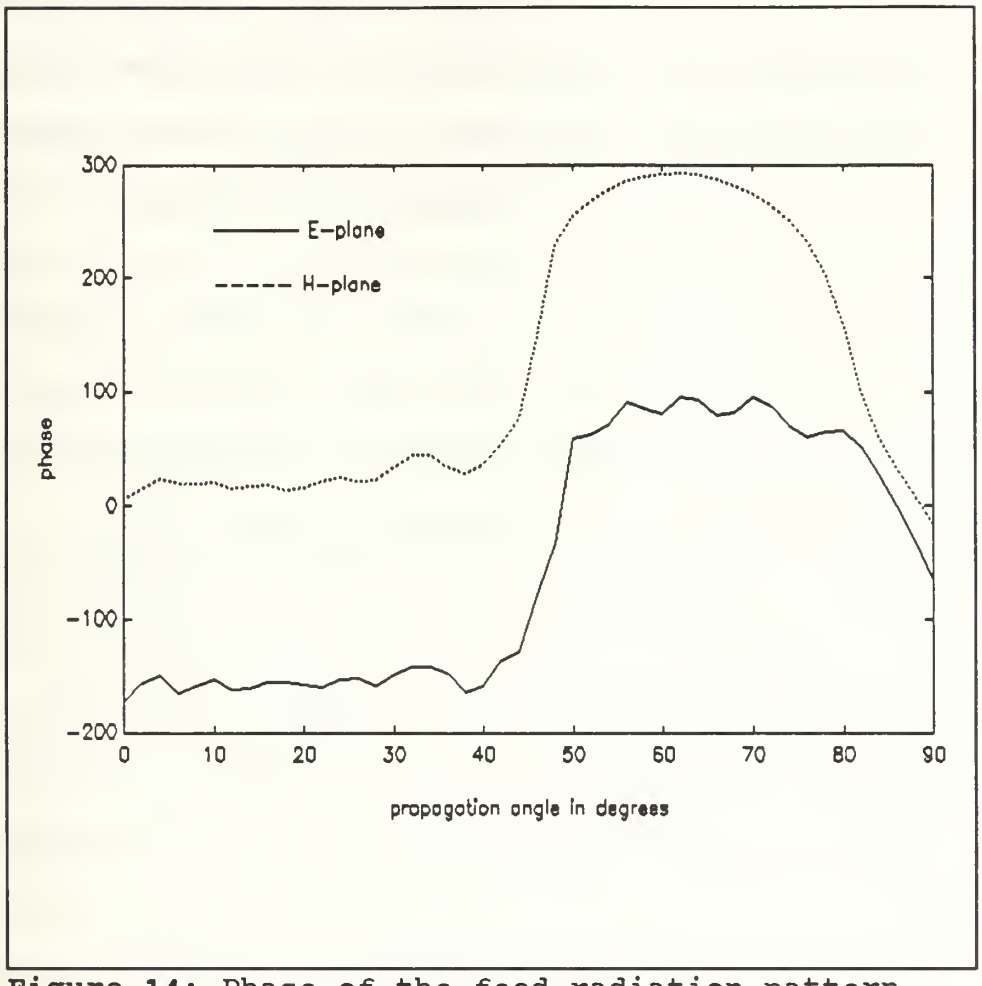

Figure 14: Phase of the feed radiation pattern.

C. INTEGRATION OF THE FEED DESIGN INTO THE REFLECTOR

The feed pattern study results provided a starting point for the feed dimensions used in the main program. It should be noted that the presence of a subreflector will affect the feed pattern. The reflected wave from the subreflector will modify the current on the feed structures as well as the main reflector. Thus, the optimum geometry for the feed when it is radiating in free space may not be the optimum when the subreflector is present. However, it was found that readjusting the feed geometry from the original

values had little effect on the overall antenna gain. More important was the subreflector location and shape. A series of calculations were done for various subreflector diameters and eccentricities. The results are summarized in Figure (15).

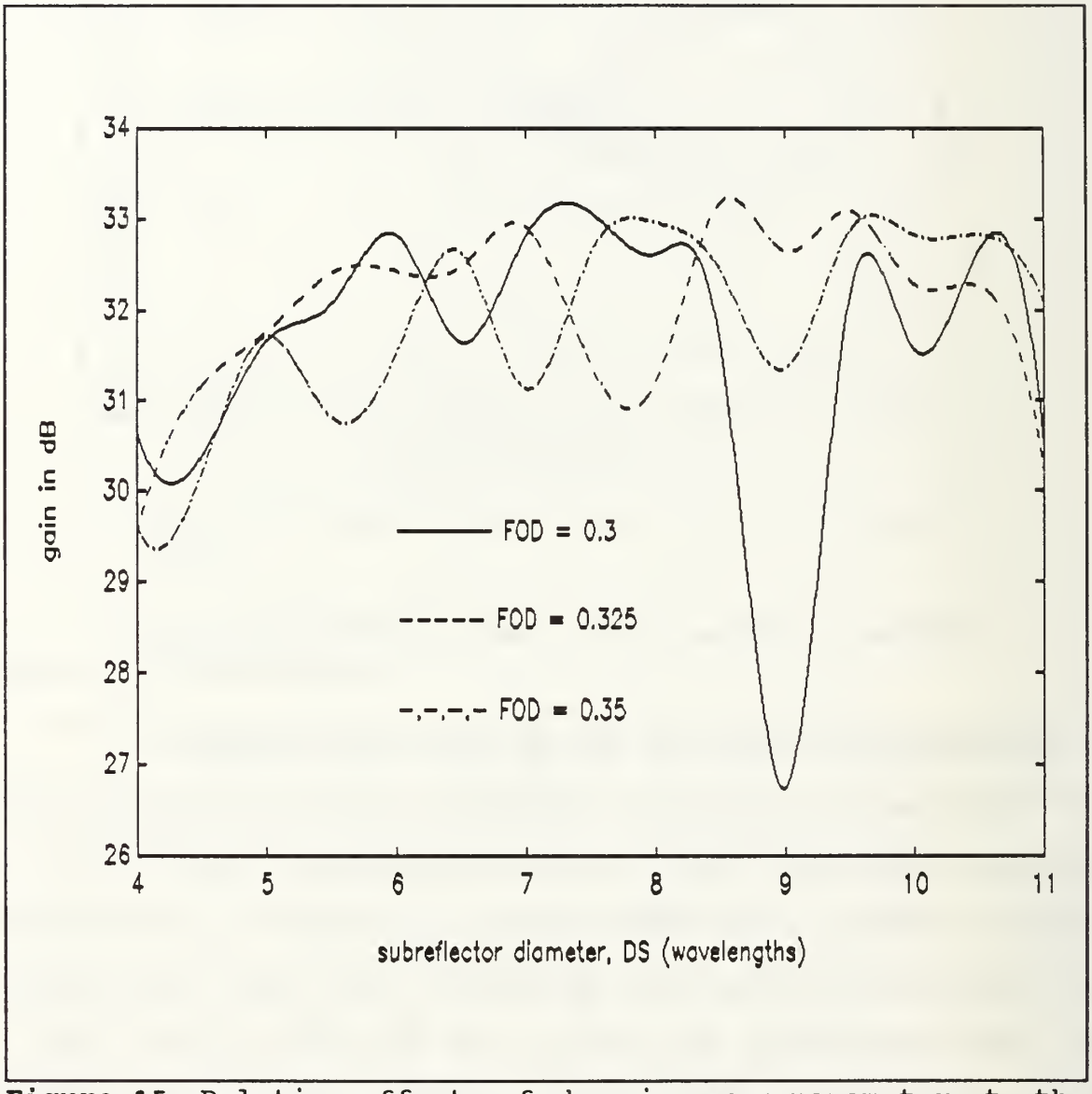

Figure 15: Relative effects of changing some parameters to the antenna performance (DM=20λ).

An interesting result of Figure (15) is that it is possible to increase the efficiency by increasing the subreflector area, even when the subreflector-to-main reflector diameter is as large as 1/3. This is the effect of tuning, i.e., adjusting the geometry so that the interactions between the reflectors add constructively rather than destructively. The trend for a small reflector antenna can be exactly opposite that predicted by geometrical optics.

As an example of the improvement that can be achieved, the pattern of a 20λ Cassegrain antenna with a single dipole feed (no parasitic dipoles and no ring) is illustrated in Figure (16) for reference. The efficiency is only 26%, primarily due to the large amount of spillover between 30° and 60°. To improve the efficiency, the feed design obtained in the last section was incorporated into the Cassegrain design. After a slight adjustment in the feed parameters, a maximum efficiency of 55.6% was achieved with a 7λ subreflector diameter. The final dimensions are given in Table 3 and the E- and H-plane radiation patterns in Figure (17). The efficiency of the basic reflector/feed configuration is approximately 50%. An increase of about 4% was obtained by readjusting the feed parameters, primarily the location of the ring. A further slight increase in the efficiency (≈0.8%)was due to the addition of the H-plane parasitic dipoles.

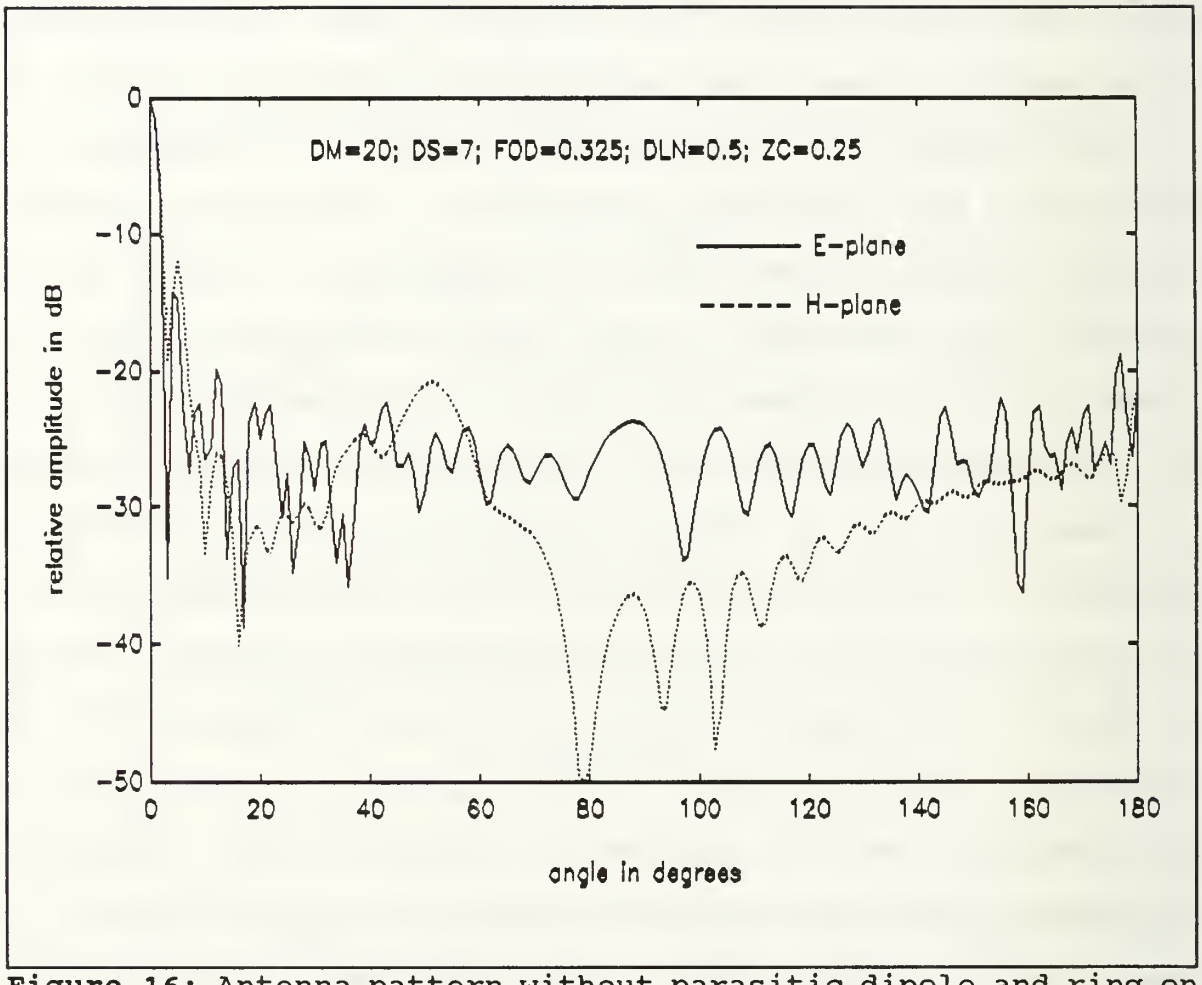

Figure 16: Antenna pattern without parasitic dipole and ring on feed.

TABLE 3

OPTIMUM PARAMETER VALUES (for Figure 17)

DM	20λ	DLN	0.5λ
DS	7λ	PLN	0.44λ
ZC	0.25λ	DDIP	0.25λ
FOD	0.325λ	AW	0.001λ
RC	1.65λ	HLGTH	0.2λ
ZR	0.25λ	DHP	0.3λ
SW	0.15λ	ZHP	0λ

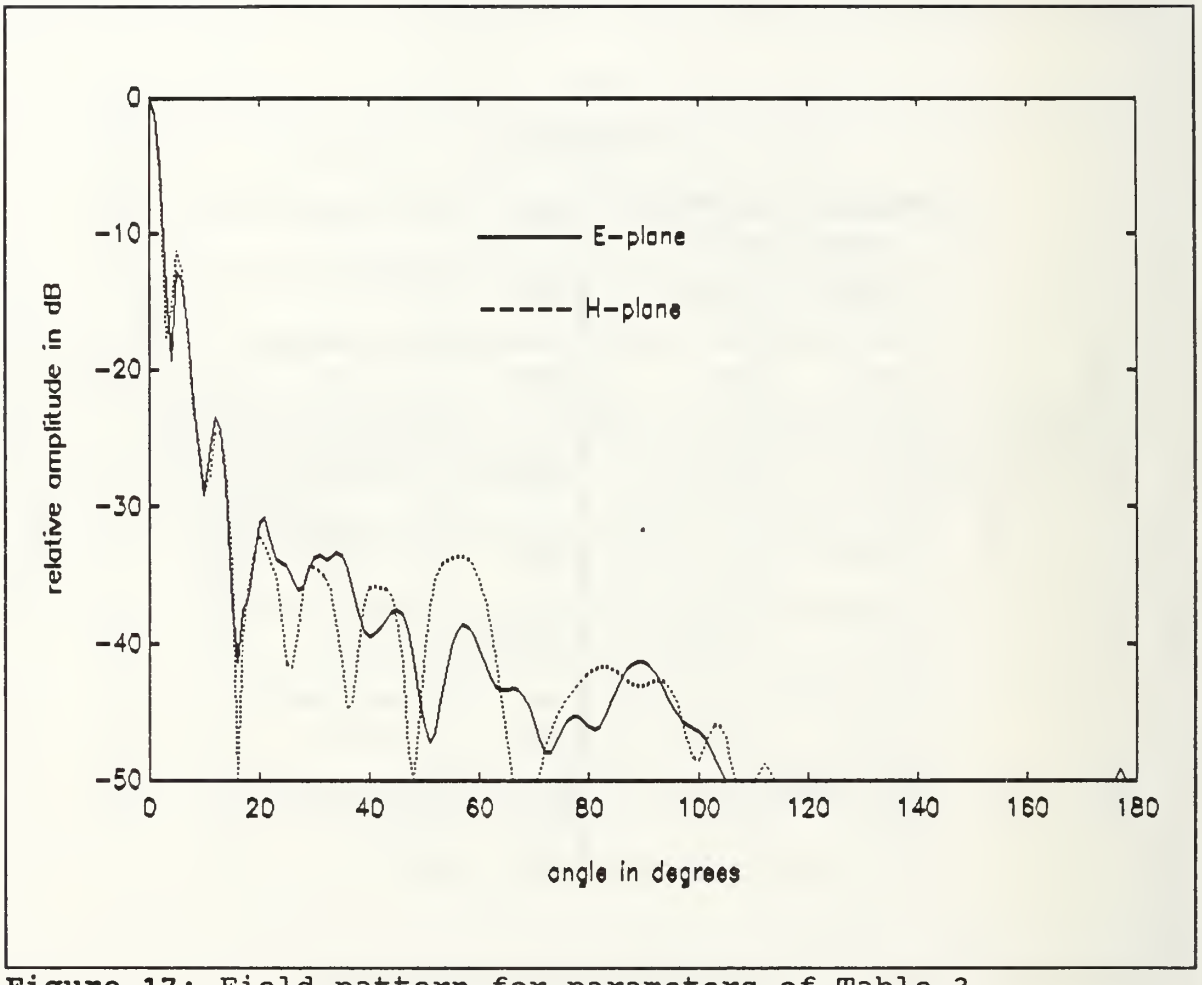

Figure 17: Field pattern for parameters of Table 3.

VI. SUMMARY AND CONCLUSIONS

The introduction of a mechanically simple low-blockage feed for small symmetric dual-reflector antennas has significantly improved its performance. From the computed results, it is apparent that in order to maximize the antenna gain, an E-plane dipole shorter than the fed dipole (director) is required. The distance of the E-plane dipole was found to be optimal at 0.25 wavelength in front of the fed dipole. Likewise, the distance of the fed dipole from the main dish has to be 0.25 wavelengths to obtain maximum gain. The ring improves the antenna's directivity but the optimum diameter and location of the ring largely depend upon the interactions of the ring to the other feed structures. The diameter of the ring may or may not be less than the length of the fed dipole. A shorter diameter however, may pose a problem in the fabrication process. The ring has to be electrically isolated from the feed and yet current continuity must be maintained on the ring.

The antenna performance generally behaved as would be expected based on the traditional ray optics approach to reflector design. But because the computer code is more accurate than ray optics, it was possible to tune the antenna geometry to minimize the loss in gain due to the surface interactions. The calculations showed that once an optimum gain had been achieved, small adjustments in the antenna feed geometry did not have a significant negative impact on antenna performance. This indicates that the design is tolerant to perturbations in the dimensions due to manufacturing and assembly errors. It may be possible that other combinations of feed

parameters are more efficient; an exhaustive study was not performed. It was determined that if there was any improvement in gain due to subreflector shaping (to compensate for feed phase error), the increase in complexity did not merit its use.

To summarize, a lightweight, compact microwave antenna design has been presented. By tuning the antenna components, an efficiency of 55% has been achieved, up from approximately 30% for a standard Cassegrain design. An antenna of this size with over 50% efficiency would be a viable candidate for such application as direct broadcast satellites and passive sensors.

APPENDIX

```
C  PROGRAM  CASTRIDIP.F
C
C  RADIATION PATTERN OF A CASSEGRAIN WITH A PARASITIC RING DIPOLE
C  FEED. THE DIPOLE LIES IN THE FOCAL PLANE AND THE CAVITY IS A
C  DISTANCE ZC  BEHIND IT. (This program utilizes a parasitic
C  dipole, two h-plane parasitic dipoles and a ring for its feed
C  configuration.)
C
C   ICALC=0 CALC CURRENTS AND FIELD
C        =1 CALC FIELDS ONLY (READ CURRENTS)
C     IMP=0 PERFECTLY CONDUCTING SURFACES
C        =1 SOME NONZERO SURFACE RESISTANCE
C   ICWRT=0 WRITE CURRENT COEFFICIENTS TO FILE pcurrent
C    IRES=0 READ RESISTIVE CORRECTIONS
C
      COMPLEX EP,ET,Z(500000),RS(1000),RW(400),B(700),C(700),U,UC
      COMPLEX ZL0(400),ZL(1500),EC,EX,ZSS(50000)
      COMPLEX EXP1,EXP2,ZSW(50000),ZWW(10000)
      COMPLEX CEXP,CONJG,CMPLX,ET1,ET2,EP1,EP2,ETW,EPW
      DIMENSION RH(400),ZH(400),XT(4),AT(4),IPS(700),NW1(4)
      DIMENSION A(400),X(400),EXP(800),ANG(800),ECP(800)
      DIMENSION ECV(800),EXV(800),PHC(800),PHX(800),NW2(4)
      DIMENSION XX(41),YY(41),XH(400),YH(400),PHA(400)
      DATA PI,START,STOP,DT/3.14159,0.,180.,1./,ICWRT/0/,IRES/1/
      DATA ICALC/0/,IPRINT/0/,IMP/0/,ITEST/1/
      DATA nt/2/,xt(1),at(1)/.5773503,1./
c     data nt/4/,xt(1),xt(2),at(1),at(2)/.33998104,.8611363115,
c    * .6521451548,.3478548451/
      OPEN(1,FILE='outgaus',status='old')
      READ(1,*) NPHI
      DO 3 K=1,NPHI
      READ(1,*) X(K),A(K)
    3 CONTINUE
      RAD=PI/180.
      BK=2.*PI
      U=(0.,1.)
      U0=(0.,0.)
      UC=-U/4./PI
      NT2=NT/2
      DO 1 K=1,NT2
      K1=NT-K+1
      AT(K1)=AT(K)
      XT(K1)=XT(K)
    1 XT(K)=-XT(K)
C
C NP10 = NUMBER OF PARABOLOID POINTS
C NP11 = NUMBER OF HYPERBOLOID POINTS
C NP12 = NUMBER OF RING POINTS
C
      MODES=1
```

```
      MHI=MODES+1
      NBLOCK=2*MODES+1
      NWIRES=1
      WRITE(6,*) 'ENTER START,STOP,DT'
      READ(5,*) START,STOP,DT
      NP10=61
      NP11=31
      NP12=3
      WRITE(6,*) 'ENTER PARA (NP10), HYPER(NP11) AND SW(NP12) PTS'
      READ(5,*) NP10,NP11,NP12
      NP1=NP10+NP11+NP12
      DM=20.
      R0=DM/2.
      DS=5.
      ZC=.25
      FOD=.3
      RC=0.5
      SW=.05
      WRITE(6,*) 'ENTER DM, DS, ZC (>0), FOD, RC, ZR AND SW'
      READ(5,*) DM,DS,ZC,FOD,RC,ZR,SW
      FM=FOD*DM
      FC=FM-ZC
C
C GENERATE PARABOLOID CONTOUR -- ONLY DO OUT TO RADIUS RGP
C
      PHIV=2.*ATAN(1./4./FOD)
      FNM=FLOAT(NP10-1)
      DO 50 I=1,NP10
      TH=FLOAT(I-1)*PHIV/FNM
      RM=2.*FM/(1.+COS(TH))
      ZH(I)=-RM*COS(TH)*BK+FC*BK
      RH(I)=RM*SIN(TH)*BK
   50 CONTINUE
C
C HYPERBOLOID (SUBREFLECTOR) CONTOUR (FC IS 2.*C)
C
      PHIR=ATAN(1./(2.*FC/DS-1./TAN(PHIV)))
      ECC=SIN((PHIV+PHIR)/2.)/SIN((PHIV-PHIR)/2.)
      AA=FC/2./ECC
      BB=AA*SQRT(ECC**2-1.)
      DO 5 I=1,NP11
      THETA=FLOAT(I-1)*PHIR/FLOAT(NP11-1)
      RR=AA*(ECC**2-1.)/(1.-ECC*COS(THETA))*BK
      ZH(I+NP10)=-RR*COS(THETA)
      RH(I+NP10)=-RR*SIN(THETA)
5     CONTINUE
C
C NEXT THE SIDEWALLS
C
      DSW=SW/FLOAT(NP12-1)
      ZRBK=ZR*BK
      IF(NP12.NE.0) THEN
```

```
      DO 7 I=1,NP12
      II=NP11+NP10+I
      XH(II)=0.
      YH(II)=0.
      RH(II)=RC*BK
      ZH(II)=FLOAT(I-1)*DSW*BK+ZRBK
7     PHA(II)=0.
      ENDIF
      NP1=NP10+NP11+NP12
C
C DIPOLE ANTENNA POINTS IN WAVELENGTHS:  AW= RADIUS; NP2= NUMBER
C OF POINTS (=NP21+NP22; NP21 MUST BE ODD); DLGTH= LENGTH;
C PLGTH IS PARASITIC ELEMENT LENGTH.
C
      AW=.001
      DLGTH=.45
      PLGTH=.44
      WRITE(6,*) 'ENTER DLN, PLN, DDIP AND AW'
      READ(5,*) DLGTH,PLGTH,DDIP,AW
      CENT=DLGTH/2.
      AK=AW*BK
      NP21=11
      NP22=0
      WRITE(6,*) 'ENTER NP21 AND NP22 (ONLY 1 DIP IF NP22=0)'
      READ(5,*) NP21,NP22
      NW1(1)=NP1+1
      NW2(1)=NP1+NP21
      NP2=NP21+NP22
      DEL=DLGTH/FLOAT(NP21-1)
      DO 10 I=1,NP21
      II=NP1+I
      YH(II)=0.
      ZH(II)=0.
      XH(II)=BK*(FLOAT(I-1)*DEL-CENT)
      RH(II)=SQRT(XH(II)**2+YH(II)**2)
      PHA(II)=ATAN2(YH(II),XH(II)+1.E-6)
10    CONTINUE
      IF(NP22.NE.0) THEN
      NWIRES=2
      NW1(2)=NP1+NP21+1
      NW2(2)=NP1+NP21+NP22
      DEL=PLGTH/FLOAT(NP22-1)
      CENT=PLGTH/2.
      DO 11 I=1,NP22
      II=NP1+NP21+I
      YH(II)=0.
      ZH(II)=DDIP*BK
      XH(II)=BK*(FLOAT(I-1)*DEL-CENT)
      RH(II)=SQRT(XH(II)**2+YH(II)**2)
      PHA(II)=ATAN2(YH(II),XH(II)+1.E-6)
11    CONTINUE
      ENDIF
```

```
C NP23=NUMBER OF H-PLANE DIPOLE POINTS
C HLGTH=H-PLANE DIPOLE LENGTH
C DHP=H-PLANE DIPOLE DISTANCE FROM FEED
C ZHP=H-PLANE DIPOLE Z COORDINATE
C NP24=NUMBER OF POINTS FOR THE OTHER H-PLANE DIPOLE
      NP23=7
      NP24=7
      HLGTH=.2
      DHP=.2
      ZHP=.001
      WRITE(6,*) 'ENTER NUMBER OF POINTS PER H-PLANE DIPOLE'
      WRITE(6,*) '(0 FOR NO H-PLANE PARASITIC DIPOLES)'
      READ(5,*) NP23
      IF(NP23.NE.0) THEN
      WRITE(6,*) 'H-PLANE DIPOLE LENGTH, DISTANCE AND LOCATION'
      READ(5,*) HLGTH,DHP,ZHP
      NWIRES=NWIRES+2
      NP24=NP23
      NP2=NP21+NP22+NP23+NP24
      NW1(3)=NP1+NP21+NP22+1
      NW2(3)=NP1+NP21+NP22+NP23
      NW1(4)=NP1+NP21+NP22+NP23+1
      NW2(4)=NP1+NP21+NP22+NP23+NP24
      DEL=HLGTH/FLOAT(NP23-1)
      CENT=HLGTH/2.
      DO 12 I=1,NP23
      I1=NP1+NP21+NP22+I
      ZH(I1)=ZHP*BK
      YH(I1)=DHP*BK
      XH(I1)=BK*(FLOAT(I-1)*DEL-CENT)
      RH(I1)=SQRT(XH(I1)**2+YH(I1)**2)
      PHA(I1)=ATAN2(YH(I1),XH(I1)+1.E-6)
      I2=I1+NP23
      ZH(I2)=ZHP*BK
      YH(I2)=-DHP*BK
      XH(I2)=BK*(FLOAT(I-1)*DEL-CENT)
      RH(I2)=SQRT(XH(I2)**2+YH(I2)**2)
      PHA(I2)=ATAN2(YH(I2),XH(I2)+1.E-6)
12    CONTINUE
      ENDIF
      CLOSE(1)
      NP=NP1+NP2
      OPEN(8,file='outcascav')
      WRITE(8,8000) DM,DS,FC,ECC,FOD,PHIR/RAD,PHIV/RAD,NP10,NP11
     *,RC,SW,NP12,DLGTH,PLGTH,DDIP,NP2,AW,MODES,NT,NPHI
      IF(NP23.NE.0) WRITE(8,8001) HLGTH,DHP,ZHP,NP23
 8000 FORMAT(//,5X,'*** CASSEGRAIN REFLECTOR SYSTEM ***',//,5X,
     *'REFLECTOR PARAMETERS (LENGTHS IN WAVELENGTHS):',/,5X,
     *'MAIN REFL DIA=',F8.3,/,5X,'SUB REFL DIA=',F8.3,/,5X,
     * '2*C=',F8.3,/,5X,'ECCENTRICITY=',F8.4,/,5X,
     * 'F/D=',F8.4,/,5X,'PHIR (DEG)=',F8.2,/,5X,
     * 'PHIV (DEG)=',F8.2,/,5X,'MAIN REFL POINTS (NP11)=',I4,/,
```

```
     * 5X,'SUB REFL POINTS (NP12)=',I4,/,5X,/,5X,
     * 'RING RADIUS=',F8.3,/,5X,'SIDEWALL LENGTH=',F8.3,/,5X,
     * 'NUMBER OF RING POINTS (NP12)=',I4,//,5X,
     * 'DIPOLE PARAMETERS:',/,5X,'FED DIPOLE LENGTH=',F8.3,/,5X,
     * 'PARASITIC DIPOLE LENGTH=',F8.3,/,5X,'SPACING=',F8.3,/,5X,
     * 'NUMBER OF DIPOLE POINTS =',I4,/,5X,'RADIUS OF DIPOLE=',
     * F8.4,//,5X,'NUMBER OF AZIMUTHAL MODES=',I3,/,5X,'NT=',I3,
     * /,5X,'NPHI=',I3)
 8001 FORMAT(/,5X,'H-PLANE DIPOLE LENGTH=',F8.3,/,5X,
     * 'H-PLANE DIPOLE DISTANCE FROM AXIS=',F8.3,/,5X,
     * 'Z POSITION OF H-FIELD DIPOLE=',F8.3,/,5X,'NUMBER OF H-FIELD
     * DIPOLE POINTS=',I3)
      IF(ISEG.EQ.0) WRITE(8,1300)
 1300 FORMAT(/,5X,'INDEX',8X,'Z(I)',10X,'RHO(I)',8x,'ZSURF')
      IF((IMP.EQ.0).OR.(IRES.NE.0)) GO TO 70
      OPEN(9,FILE='difdat')
      READ(9,*) ID
      WRITE(6,*) 'ID=',ID
      DO 75 I=1,ID
      READ(9,*) II,RI,YY(I),DUM
      IF(YY(I).LT.0.) YY(I)=0.
75    CONTINUE
      XXI=1./FLOAT(ID-1)
      DO 15 II=1,ID
      XX(II)=XXI*FLOAT(II-1)
15    CONTINUE
      WRITE(6,*) 'SURFACE IMPEDANCE VALUES READ'
70    CONTINUE
      DO 52 I=1,NP1
      IF(ABS(ZH(I)).LT..001) ZH(I)=0.
      IF(ABS(RH(I)).LT..001) RH(I)=0.
      ZL0(I)=(0.,0.)
      ZHB=ZH(I)/BK
      RHB=RH(I)/BK
c     if(rhb.ge.10.) zl0(i)=(.2,0.)
C
C NONZERO SURFACE IMPEDANCES IF IMP > 0
C
      IF((IMP.EQ.0).OR.(IRES.NE.0)) GO TO 51
      IF(I.GT.NP10) GO TO 51
C
C USE THE EXACT RESISTIVE CORRECTIONS -- INTERPOLATE BETWEEN
C DATA POINTS.
C
      UU=RHB/R0
      CALL INTERP(UU,VV,XX,YY,ID)
      ZL0(I)=VV
   51 CONTINUE
      WRITE(8,8004) I,ZHB,RHB,ZL0(I)
   52 CONTINUE
 8004 FORMAT(6X,I4,4X,F8.3,8X,F8.3,6X,2F8.4)
      WRITE(8,1310)
```

```
 1310 FORMAT(/,5X,'DIPOLE COORDINATES:',//,
     * 5X,'INDEX',8X,'Z(I)',10X,'RHO(I)',10X,'PHI PLN')
      DO 53 I=NP1+1,NP
      IF(ABS(ZH(I)).LT..001) ZH(I)=0.
      IF(ABS(RH(I)).LT..001) RH(I)=0.
      ZHB=ZH(I)/BK
      RHB=RH(I)/BK
      PHB=PHA(I)/RAD
   53 WRITE(8,8005) I,ZHB,RHB,PHB
 8005 FORMAT(6X,I4,4X,F8.3,8X,F8.3,9X,F8.2)
  799 CONTINUE
      IF(ITEST.EQ.0) GO TO 9998
      write(6,*) 'geometry defined'
C
C DEFINE DIMENSIONS OF THE IMPEDANCE MATRIX BLOCKS
C
      MT1=NP1-2
      MP1=NP1-1
      N=MP1+MT1
      MT2=NP2-2
      NSURF=NBLOCK*N
      NSW=NSURF+MT2
      NROW=NSW
      WRITE(6,*) 'NP1,NP2,NSURF,NROW=',NP1,NP2,NSURF,NROW
      WRITE(6,*) 'MT2 SHOULD BE ODD -- MT2=',MT2
      IF(ITEST.EQ.0) GO TO 9998
      IF(ICALC.EQ.0) THEN
C
C COMPUTE IMPEDANCE MATRIX ELEMENTS
C
      CALL ZMATWW(NWIRES,NW1,NW2,XH,YH,RH,ZH,NT,XT,AT,AK,ZWW)
      CALL ZASMB0(NP1,NP2,MODES,Z,ZWW)
      write(6,*) 'wire impedance computed'
      IF(IMP.NE.0) THEN
      CALL ZLOAD(NP1,RH,ZH,ZL0,ZL)
      WRITE(6,*) 'RESISTIVE SURFACE IMPEDANCE MATRIX COMPUTED'
      ENDIF
      DO 400 M=1,MHI
      NM=M-1
      CALL ZMATSS(NM,NM,NP10,NP11,NP12,NPHI,NT,RH,ZH,X,A,XT,AT,ZSS)
c     if(nm.ne.0) then
c     write(8,*) 'print zss'
c     do 669 kk=1,n
c     do 669 jj=1,n
c     jk=jj+(kk-1)*n
c669  write(8,*) nm,jj,kk,zss(jk)
c     endif
      IF(IMP.NE.0) CALL ZTOT(MT1,MP1,ZL,ZSS)
      CALL ZMATSW(NWIRES,NW1,NW2,NP10,NP11,NP12,XH,YH,RH,ZH,
     * NT,XT,AT,NPHI,X,A,NM,AK,ZSW)
c     if(nm.ne.0) then
c     write(8,*) 'printing positive zsw'
```

```
c     do 666 kk=1,mt2
c     do 666 jj=1,n
c     jk=jj+(kk-1)*n
c666  write(8,*) nm,jj,kk,zsw(jk)
c     endif
      CALL ZASMBN(NP1,NP2,MODES,NM,Z,ZSS,ZSW)
      IF(NM.EQ.0) GO TO 400
      NMN=-NM
      CALL ZMATSW(NWIRES,NW1,NW2,NP10,NP11,NP12,XH,YH,RH,ZH,
     * NT,XT,AT,NPHI,X,A,NMN,AK,ZSW)
      CALL ZASMBN(NP1,NP2,MODES,NMN,Z,ZSS,ZSW)
  400 CONTINUE
      write(6,*) 'z filled'
      CALL DECOMP(NROW,IPS,Z)
      write(6,*) 'z decomposed'
C
C EXCITATION ELEMENTS (NONZERO FOR THE DIPOLE ONLY)
C
      DO 40 I=1,NROW
   40 B(I)=(0.,0.)
      I0=NSURF+(NP21-1)/2
      B(I0)=(1.,0.)
      CALL SOLVE(NROW,IPS,Z,B,C)
      do 665 ii=1,nrow
  665 write(6,*) ii,c(ii)
      IF((ICWRT.EQ.0).AND.(ICALC.EQ.0)) THEN
C
C WRITE CURRENTS ON DISC FOR PATTERN INTEGRATION
c (program 'cavarchint.f')
C
       OPEN(3,file='pcurrent')
       WRITE(3,*) DM,AW,ZC,RC,DS,NP1,NP2,NBLOCK,NWIRES
       WRITE(3,*) NP,MT1,MP1,N,MT2,NSURF,NROW,MHI,MODES
       WRITE(3,*) (XH(I),I=1,NP)
       WRITE(3,*) (yh(I),I=1,NP)
       WRITE(3,*) (zh(I),I=1,NP)
       WRITE(3,*) (rh(I),I=1,NP)
       WRITE(3,*) (pha(I),I=1,NP)
       WRITE(3,*) (NW1(I),I=1,NWIRES)
       WRITE(3,*) (NW2(I),I=1,NWIRES)
       WRITE(3,*) (C(i),I=1,NROW)
      ENDIF
      ENDIF
C
C IF ICALC.NE.0 THEN READ CURRENT COEFFICIENTS FROM DISK FILE
C
      IF(ICALC.NE.0) THEN
      OPEN(3,file='pcurrent',STATUS='OLD')
       READ(3,*) DMX,AWX,ZCX,RCX,DSX,NP1X,NP2X,NBLX,NWX
       READ(3,*) NPX,MT1X,MP1X,NX,MT2X,NSX,NRX,MHIX,MODESX
       READ(3,*) (xh(i),i=1,np)
       READ(3,*) (yh(i),i=1,np)
```

```
       READ(3,*) (zh(i),i=1,np)
       READ(3,*) (rh(i),i=1,np)
       READ(3,*) (pha(i),i=1,np)
       READ(3,*) (nw1(i),i=1,nwires)
       READ(3,*) (nw2(i),i=1,nwires)
       READ(3,*) (c(i),i=1,nrow)
      CLOSE(3)
      write(6,*) 'data read from pcurrent'
      do 909 i=1,np
909   write(6,*) 'i,rh,zh=',i,rh(i)/bk,zh(i)/bk
      ENDIF
      IT=INT((STOP-START)/DT)+1
C
C RECEIVER PHI CUTS: DO 0 AND 90 (E- AND H- PLANES)
C
      DO 501 IP=1,2
      ECX=1.e-10
      PHR0=0.
      IF(IP.EQ.2) PHR0=RAD*90.
      DO 500 I=1,IT
      THETA=FLOAT(I-1)*DT+START
      THR=THETA*RAD
      PHR=PHR0
      IF(THETA.LE.180.) GO TO 99
      THR=(360.-THETA)*RAD
      PHR=PHR0+PI
   99 CONTINUE
c     write(6,*) 'theta,phi=',theta,phr/rad
      ET1=U0
      ET2=U0
      EP1=U0
      EP2=U0
      ETW=U0
      EPW=U0
C
C DIPOLE FIELD
C
      CALL PLANEW(NWIRES,NW1,NW2,NP1,NP2,XH,YH,ZH,THR,PHR,RW)
      DO 210 L=1,MT2
      ETW=ETW+RW(L)*C(L+NSURF)
  210 EPW=EPW+RW(L+MT2)*C(L+NSURF)
C
C REFLECTOR AND CAVITY FIELD CONTRIBUTIONS
C
      DO 300 M=1,MHI
      NM=M-1
      EXP1=CEXP(CMPLX(0.,FLOAT(NM)*PHR))
      EXP2=CONJG(EXP1)
      CALL PLANES(NM,NP10,NP11,NP12,NT,RH,ZH,XT,AT,THR,RS)
      NTOP1=MODES-NM
      NTOP2=NBLOCK-(NTOP1+1)
      NS2=NTOP1*N
```

```
      NS1=NTOP2*N
      DO 250 L=1,MT1
      ET1=ET1+RS(L)*C(L+NS1)*EXP1
      EP1=EP1+RS(L+N)*C(L+NS1)*EXP1
      IF(NM.EQ.0) GO TO 250
      ET1=ET1+RS(L)*C(L+NS2)*EXP2
      EP1=EP1-RS(L+N)*C(L+NS2)*EXP2
  250 CONTINUE
      DO 260 L=1,MP1
      ET2=ET2+RS(L+MT1)*C(L+NS1+MT1)*EXP1
      EP2=EP2+RS(L+MT1+N)*C(L+NS1+MT1)*EXP1
      IF(NM.EQ.0) GO TO 260
      ET2=ET2-RS(L+MT1)*C(L+NS2+MT1)*EXP2
      EP2=EP2+RS(L+MT1+N)*C(L+NS2+MT1)*EXP2
  260 CONTINUE
  300 CONTINUE
      ET=UC*(ET1+ET2+ETW)
      EP=UC*(EP1+EP2+EPW)
      EC=ET
      EX=EP
      ECV(I)=CABS(EC)
      EXV(I)=CABS(EX)
      ECR=REAL(EC)
      ECI=AIMAG(EC)
      EXR=REAL(EX)
      EXI=AIMAG(EX)
      PHC(I)=ATAN2(ECI,ECR+1.e-10)/RAD
      PHX(I)=ATAN2(EXI,EXR+1.e-10)/RAD
      ANG(I)=THETA
      ECX=AMAX1(ECX,ECV(I),EXV(I))
  500 CONTINUE
      WRITE(8,103) PHR/RAD,ECX
  103 FORMAT(/,5X, 'PHI OF RECEIVER (DEG)=',F8.2,/,5X,
     * 'MAXIMUM FIELD VALUE (V/M)=',E15.5)
      DO 600 I=1,IT
      ECP(I)=(ECV(I)/ECX)**2
      EXP(I)=(EXV(I)/ECX)**2
      ECP(I)=AMAX1(ECP(I),.00001)
      EXP(I)=AMAX1(EXP(I),.00001)
      ECP(I)=10.*ALOG10(ECP(I))
      EXP(I)=10.*ALOG10(EXP(I))
  600 CONTINUE
      IF(IPRINT.NE.0) GO TO 310
      WRITE(8,5015)
 5015 FORMAT(///,7X,'ANGLE',15X,'CO-POL',25X,'X-POL',/,7X,
     *'(DEG)',4X,2('(VOLTS)',4X,'(DEG)',3X,'(DB-REL)',4X))
      DO 9000 L=1,IT
      WRITE(8,5016) ANG(L),ECV(L),PHC(L),ECP(L),EXV(L),PHX(L)
     *,EXP(L)
 5016 FORMAT(5X,F6.1,3X,2(F8.4,3X,F7.1,3X,F7.2,3X))
 9000 CONTINUE
  310 CONTINUE
```

```
      IF(IP.EQ.1) THEN
      OPEN(2,file='cang.m')
      OPEN(3,file='ccpole.m')
      OPEN(4,file='cxpole.m')
      DO 9097 I=1,IT
      WRITE(2,5019) ANG(I)
      WRITE(3,5019) ECP(I)
 9097 WRITE(4,5019) EXP(I)
      CLOSE(2)
      CLOSE(3)
      CLOSE(4)
      ENDIF
      IF(IP.EQ.2) THEN
      OPEN(3,file='ccpolh.m')
      OPEN(4,file='cxpolh.m')
      DO 9098 I=1,IT
      WRITE(3,5019) ECP(I)
 9098 WRITE(4,5019) EXP(I)
      CLOSE(3)
      CLOSE(4)
      ENDIF
501   CONTINUE
5019  FORMAT(F8.3)
9998  STOP
      END
      SUBROUTINE SOLVE(N,IPS,UL,B,X)
      COMPLEX UL(500000),B(700),X(700),SUM
      DIMENSION IPS(700)
      NP1=N+1
      IP=IPS(1)
      X(1)=B(IP)
      DO 2 I=2,N
      IP=IPS(I)
      IPB=IP
      IM1=I-1
      SUM=(0.,0.)
      DO 1 J=1,IM1
      SUM=SUM+UL(IP)*X(J)
    1 IP=IP+N
    2 X(I)=B(IPB)-SUM
      K2=N*(N-1)
      IP=IPS(N)+K2
      X(N)=X(N)/UL(IP)
      DO 4 IBACK=2,N
      I=NP1-IBACK
      K2=K2-N
      IPI=IPS(I)+K2
      IP1=I+1
      SUM=(0.,0.)
      IP=IPI
      DO 3 J=IP1,N
      IP=IP+N
```

```
 3 SUM=SUM+UL(IP)*X(J)
 4 X(I)=(X(I)-SUM)/UL(IPI)
   RETURN
   END
   SUBROUTINE DECOMP(N,IPS,UL)
   COMPLEX UL(500000),PIVOT,EM
   DIMENSION SCL(700),IPS(700)
   DO 5 I=1,N
   IPS(I)=I
   RN=0.
   J1=I
   DO 2 J=1,N
   ULM=ABS(REAL(UL(J1)))+ABS(AIMAG(UL(J1)))
   J1=J1+N
   IF(RN-ULM) 1,2,2
 1 RN=ULM
 2 CONTINUE
   SCL(I)=1./RN
 5 CONTINUE
   NM1=N-1
   K2=0
   DO 17 K=1,NM1
   BIG=0.
   DO 11 I=K,N
   IP=IPS(I)
   IPK=IP+K2
   SIZE=(ABS(REAL(UL(IPK)))+ABS(AIMAG(UL(IPK))))*SCL(IP)
   IF(SIZE-BIG) 11,11,10
10 BIG=SIZE
   IPV=I
11 CONTINUE
   IF(IPV-K) 14,15,14
14 J=IPS(K)
   IPS(K)=IPS(IPV)
   IPS(IPV)=J
15 KPP=IPS(K)+K2
   PIVOT=UL(KPP)
   KP1=K+1
   DO 16 I=KP1,N
   KP=KPP
   IP=IPS(I)+K2
   EM=-UL(IP)/PIVOT
18 UL(IP)=-EM
   DO 16 J=KP1,N
   IP=IP+N
   KP=KP+N
   UL(IP)=UL(IP)+EM*UL(KP)
16 CONTINUE
   K2=K2+N
17 CONTINUE
   RETURN
   END
```

```
      FUNCTION BLOG(X)
      IF(X.GT..1) GO TO 1
      X2=X*X
      BLOG=((.075*X2-.1666667)*X2+1.)*X
      RETURN
    1 BLOG=ALOG(X+SQRT(1.+X*X))
      RETURN
      END
      SUBROUTINE ZLOAD(NP,RH,ZH,Z0,Z)
C
C COMPUTES IMPEDANCE MATRIX ELEMENTS FOR LOADED BODIES OF REV
C Z0(I) IS THE SURF IMPEDANCE OF THE ITH SEGMENT (NP-1 SEGMENTS)
C Z(.) ARE THE IMPEDANCE MATRIX TERMS (TRIDIAGONAL FOR T-T
C SUBMATRIX; DIAGONAL FOR P-P SUBMATRIX). STORED IN COL VECTOR.
C
      COMPLEX C1,C2,Z0(400),Z(1500),X1,X2,X3,Y1,Y2,Y3,FN(400)
      COMPLEX U1,U2,U3,XI,YI
      DIMENSION RH(400),ZH(400),RS(400),D(400),SV(400)
      PI=3.14159
      MT=NP-2
      MP=NP-1
      N=MT+MP
      DO 10 IP=2,NP
      II=IP-1
      DR=RH(IP)-RH(II)
      DZ=ZH(IP)-ZH(II)
      D(II)=SQRT(DR*DR+DZ*DZ)
      SV(II)=DR/D(II)
      RS(II)=.5*(RH(IP)+RH(II))
      DS=D(II)*SV(II)/2.
      Q1=RS(II)+DS
      Q2=RS(II)-DS
      FN(II)=1.
      IF((ABS(Q2).GT.1.E-6).AND.(ABS(Q1).GT.1.E-6))
     * FN(II)=ALOG(Q1/Q2)
   10 CONTINUE
      L0=MT*3-2
      DO 20 I=1,MP
      C1=PI*Z0(I)
      IF(I.EQ.MP) GO TO 80
      KI=2
      IF(I.EQ.1) KI=1
      IF(I.EQ.MT) KI=3
      II=I+1
      C2=PI*Z0(II)
      A=SV(I)
      IF(ABS(A).LT.1.E-6) GO TO 41
      X1=C1*FN(I)/2./A
      X2=C1*2./A*(1.-RS(I)*FN(I)/D(I)/A)
      X3=-X2*RS(I)/D(I)/A
      GO TO 42
   41 CONTINUE
```

```
      X1=C1/2./RS(I)*D(I)
      X2=(0.,0.)
      X3=C1*D(I)/6./RS(I)
   42 CONTINUE
      A=SV(II)
      IF(ABS(A).LT.1.E-6) GO TO 45
      Y1=C2*FN(II)/2./A
      Y2=C2*2./A*(1.-RS(II)*FN(II)/D(II)/A)
      Y3=-Y2*RS(II)/D(II)/A
      GO TO 40
   45 CONTINUE
      Y1=C2/2./RS(II)*D(II)
      Y2=(0.,0.)
      Y3=C2*D(II)/6./RS(II)
   40 CONTINUE
C
C DEFINE TRIDIAGONAL ELEMENTS FOR T-T SUBMATRIX (STORED IN COLS)
C (U1- DIAG; U2- LOWER; U3- UPPER)
C
      XI=X1+X2+X3
      YI=Y1-Y2+Y3
      IF(KI.EQ.1) XI=C1/SV(I)
C     IF(KI.EQ.3) YI=C2/SV(II)
      U1=XI+YI
      U2=X1-X3
      U3=Y1-Y3
      L=2+(I-2)*3
      IF(KI.EQ.1) L=0
      L1=L+1
      L2=L+2
      L3=L+3
      go to (50,60,70),ki
   50 Z(L1)=U1
      Z(L2)=U2
      GO TO 80
   60 Z(L1)=U3
      Z(L2)=U1
      Z(L3)=U2
      GO TO 80
   70 Z(L1)=U3
      Z(L2)=U1
   80 Z(L0+I)=2.*C1*D(I)/RS(I)
   20 CONTINUE
      RETURN
      END
      SUBROUTINE ZTOT(MT,MP,ZL,Z)
C
C ADDS THE SURF IMPEDANCE TERMS TO THE TRIDIAGONAL ELEMENTS OF
C THE BOR IMPEDANCE MATRIX Z.
C
      COMPLEX ZL(700),Z(50000)
      N=MT+MP
```

```
      M0=MT*3-2
      DO 100 I=1,MP
      L0=MT*N+(I-1)*N+MT
      IF(I.EQ.MP) GO TO 80
      KI=2
      IF(I.EQ.1) KI=1
      IF(I.EQ.MT) KI=3
      L2=(I-1)*N+I
      L1=L2-1
      L3=L2+1
      M=2+3*(I-2)
      IF(KI.EQ.1) M=0
      M1=M+1
      M2=M+2
      M3=M+3
      go to (50,60,70),ki
   50 Z(L2)=Z(L2)+ZL(M1)
      Z(L3)=Z(L3)+ZL(M2)
      GO TO 80
   60 Z(L1)=Z(L1)+ZL(M1)
      Z(L2)=Z(L2)+ZL(M2)
      Z(L3)=Z(L3)+ZL(M3)
      GO TO 80
   70 Z(L1)=Z(L1)+ZL(M1)
      Z(L2)=Z(L2)+ZL(M2)
   80 Z(L0+I)=Z(L0+I)+ZL(M0+I)
  100 CONTINUE
      RETURN
      END
      subroutine interp(u,v,x,y,nn)
c program to interpolate linearly between arrays of x and y
c values (with dimensions nn).  u is specified and v is returned
c uniform sampling in x (the ordinate) is assumed.
      dimension x(nn),y(nn)
      delx=x(2)-x(1)
      n1=int(u/delx)+1
      n2=n1+1
      dely=y(n2)-y(n1)
      sgn=sign(1.,dely)
      dely=abs(dely)
      alpha=u-x(n1)
      zeta=dely*alpha/delx
      v=y(n1)+sgn*zeta
      return
      end
      SUBROUTINE PLANEW(NWIRES,NW1,NW2,NP1,NP2,XH,YH,ZH,
     * THR,PHR,R)
C
C  PLANE WAVE EXCITATION VECTOR ELEMENTS FOR WIRE AND
C  ATTACHMENT SEGMENT. INCIDENCE DIRECTION IS (THR,PHR).
C    - ONLY ONE INCIDENCE ANGLE PER CALL
C    - WIRE DOES NOT HAVE TO LIE IN THE Z=0 PLANE
```

```
C
      COMPLEX U0,AA,BB,C,R(400),CEXP,EXP,FI1,FI2,SI,DI,CMPLX
      DIMENSION ZH(400),NS(4),NW1(4),NW2(4),XH(400),YH(400)
      MP2=NP2-1
      MT2=NP2-2
      MT22=2*MT2
      DO 5 L=1,NWIRES
    5 NS(L)=NW2(L)-NW1(L)+1
      U0=(0.,0.)
      CC=COS(THR)
      SS=SIN(THR)
      CP=COS(PHR)
      SP=SIN(PHR)
      UP=SS*CP
      VP=SS*SP
      WP=CC
      DO 12 IP=1,MP2
      II=IP+NP1
      I=II+1
      ZS=.5*(ZH(I)+ZH(II))
      XS=.5*(XH(I)+XH(II))
      YS=.5*(YH(I)+YH(II))
      DX=XH(I)-XH(II)
      DY=YH(I)-YH(II)
      D1=SQRT(DX**2+DY**2)
      SU=DY/D1
      CU=DX/D1
C FOR WIRES IN PERPENDICULAR TO Z SIN(V)=1 AND COS(V)=0
      SV=1.0
      CV=0.0
C
C WIRE SEGMENT CALCULATIONS
C
      A=UP*CU+VP*SU
      B=UP*XS+VP*YS+WP*ZS
      C=CMPLX(0.,A)
      EXP=CEXP(CMPLX(0.,B))
      AA=CC*(CU*CP+SU*SP)
      BB=SU*CP-SP*CU
      PSI=D1*A/2.
      IF(PSI.NE.0.) GO TO 60
      SINC=1.
      GO TO 61
   60 SINC=SIN(PSI)/PSI
   61 COSP=COS(PSI)
      FI1=SINC*D1*EXP/2.
      FI2=(0.,0.)
      IF(ABS(A).LT.1.E-4) GO TO 62
      CSP=COSP-SINC
      IF(ABS(CSP).LT.1.E-4) GO TO 62
      FI2=EXP/C*CSP
   62 CONTINUE
```

```
      SI=FI1+FI2
      DI=FI1-FI2
C
C R-WIRE-THETA
C
      IF(IP.EQ.MP2) GO TO 10
      R(IP)=AA*SI
      R(IP+MT2)=BB*SI
   10 CONTINUE
C
C R-WIRE-PHI
C
   14 IF(IP.EQ.1) GO TO 12
      R(IP-1)=R(IP-1)+AA*DI
      R(IP-1+MT2)=R(IP-1+MT2)+BB*DI
   12 CONTINUE
C
C WRITE OVER DUMMY WIRE SEGMENTS
C
c     IF(NWIRES.EQ.1) GO TO 210
c     NSPTS=0
c     DO 209 L=1,NWIRES-1
c     NSPTS=NSPTS+NS(L)
c     IN=NSPTS-2
c     R(IN+1)=U0
c     R(IN+2)=U0
c     IN=IN+MT2
c     R(IN+1)=U0
c     R(IN+2)=U0
c 209 CONTINUE
  210 RETURN
      END
      SUBROUTINE PLANES(M1,NP0,NP1,NP2,NT,RH,ZH,XT,AT,THR,R)
C
C PLANE WAVE EXCITATION VECTOR FOR BOR ELEMENTS.
C NO CHANGE FROM HARRINGTON'S ORIGINAL PROGRAM OTHER THAN
C
C ** ONLY ONE MODE PER CALL **
C
      COMPLEX R(1000),U,U1,UA,UB,FA(50),FB(50),F2A,F2B,F1A,F1B
      COMPLEX U2,U3,U4,U5,CMPLX
      DIMENSION RH(400),ZH(400),XT(4),AT(4)
      DIMENSION R2(4),Z2(4),BJ(5000)
      U=(0.,1.)
      U1=3.141593*U**M1
      NF=1
      M2=M1
      NP=NP0+NP1+NP2
      NRF=NP0+NP1
      MP=NP-1
      MT=MP-1
      N=MT+MP
```

```
      N2=2*N
      CC=COS(THR)
      SS=SIN(THR)
      M3=M1+1
      M4=M2+3
      IF(M1.EQ.0) M3=2
      M5=M1+2
      M6=M2+2
      DO 12 IP=1,MP
      K2=IP
      I=IP+1
      DR=.5*(RH(I)-RH(IP))
      DZ=.5*(ZH(I)-ZH(IP))
      D1=SQRT(DR*DR+DZ*DZ)
      R1=.25*(RH(I)+RH(IP))
      IF(ABS(R1).LT.1.E-5) R1=1.
      Z1=.5*(ZH(I)+ZH(IP))
      DR=.5*DR
      D2=DR/R1
      DO 13 L=1,NT
      R2(L)=R1+DR*XT(L)
      Z2(L)=Z1+DZ*XT(L)
   13 CONTINUE
      D3=DR*CC
      D4=-DZ*SS
      D5=D1*CC
      DO 23 M=M3,M4
      FA(M)=0.
      FB(M)=0.
   23 CONTINUE
      DO 15 L=1,NT
      X=SS*R2(L)
      IF(X.GT..5E-7) GO TO 19
      DO 20 M=M3,M4
      BJ(M)=0.
   20 CONTINUE
      BJ(2)=1.
      S=1.
      GO TO 18
   19 M=2.8*X+14.-2./X
      IF(X.LT..5) M=11.8+ALOG10(X)
      IF(M.LT.M4) M=M4
      BJ(M)=0.
      JM=M-1
      BJ(JM)=1.
      DO 16 J=4,M
      J2=JM
      JM=JM-1
      J1=JM-1
      BJ(JM)=J1/X*BJ(J2)-BJ(JM+2)
   16 CONTINUE
      S=0.
```

```
      IF(M.LE.4) GO TO 24
      DO 17 J=4,M,2
      S=S+BJ(J)
   17 CONTINUE
   24 S=BJ(2)+2.*S
   18 ARG=Z2(L)*CC
      UA=AT(L)/S*CMPLX(COS(ARG),SIN(ARG))
      UB=XT(L)*UA
      DO 25 M=M3,M4
      FA(M)=BJ(M)*UA+FA(M)
      FB(M)=BJ(M)*UB+FB(M)
   25 CONTINUE
   15 CONTINUE
      IF(M1.NE.0) GO TO 26
      FA(1)=- FA(3)
      FB(1)=- FB(3)
   26 UA=U1
      DO 27 M=M5,M6
      M7=M-1
      M8=M+1
      F2A=UA*(FA(M8)+FA(M7))
      F2B=UA*(FB(M8)+FB(M7))
      UB=U*UA
      F1A=UB*(FA(M8)-FA(M7))
      F1B=UB*(FB(M8)-FB(M7))
      U4=D4*UA
      U2=D3*F1A+U4*FA(M)
      U3=D3*F1B+U4*FB(M)
      U4=DR*F2A
      U5=DR*F2B
      K1=K2-1
      K4=K1+N
      K5=K2+N
      R(K2+MT)=-D5*(F2A+D2*F2B)
      R(K5+MT)=D1*(F1A+D2*F1B)
      IF(IP.EQ.1) GO TO 21
      R(K1)=R(K1)+U2-U3
      R(K4)=R(K4)+U4-U5
      IF(IP.EQ.MP) GO TO 22
   21 R(K2)=U2+U3
      R(K5)=U4+U5
   22 K2=K2+N2
      UA=UB
   27 CONTINUE
   12 CONTINUE
C     R(NP0-1)=(0.,0.)
C     R(NP0)=(0.,0.)
C     R(NP0+MT)=(0.,0.)
C     R(NRF-1)=(0.,0.)
C     R(NRF)=(0.,0.)
C     R(NRF+MT)=(0.,0.)
   99 RETURN
```

```
      END
      SUBROUTINE ZMATSS(M1,M2,NP0,NP1,NP2,NPHI
     *NT,RH,ZH,X,A,XT,AT,Z)
C
C ********  THREE DETACHED SURFACES  ***********
C SURFACE-SURFACE IMPEDANCE ELEMENTS. REMAINS UNCHANGED FROM
C HARRINGTON EXCEPT MULTIPLE SURFACES ARE PERMITTED. THE FIRST
c SURFACE HAS NP0 POINTS, THE SECOND NP1 POINTS AND THE THIRD NP2.
C NP0 PARABOLOID PTS; NP1 HYPERBOLOID PTS; NP2 CAVITY PTS.
C
      COMPLEX Z(50000),U1,U2,U3,U4,U5,U6,U7,U8,U9,UA,UB
      COMPLEX G6A(4),G4B(4),G5B(4),G6B(4),H4A,H5A,H6A,H4B,H5B
      COMPLEX CMPLX,H6B,UC,UD,GA(400),GB(400),G4A(4),G5A(4)
      DIMENSION RH(400),ZH(400),X(400),A(400),AT(4),RS(400),ZS(400)
      DIMENSION D(400),DR(400),DZ(400),DM(400),C2(400)
      DIMENSION C4(400),C5(400),C6(400),Z7(4),R7(4),Z8(4),R8(4)
      DIMENSION XT(4),Z2(4),C3(400),R2(4)
      CT=2.
      CP=.1
      NP=NP0+NP1+NP2
      NRF=NP0+NP1
      DO 10 I=2,NP
      I2=I-1
      RS(I2)=.5*(RH(I)+RH(I2))
      ZS(I2)=.5*(ZH(I)+ZH(I2))
      D1=.5*(RH(I)-RH(I2))
      D2=.5*(ZH(I)-ZH(I2))
      D(I2)=SQRT(D1*D1+D2*D2)
      DR(I2)=D1
      DZ(I2)=D2
      DM(I2)=D(I2)/RS(I2)
   10 CONTINUE
      M3=M2-M1+1
      M4=M1-1
      PI2=1.570796
      DO 11 K=1,NPHI
      PH=PI2*(X(K)+1.)
      C2(K)=PH*PH
      SN=SIN(.5*PH)
      C3(K)=4.*SN*SN
      A1=PI2*A(K)
      D4=.5*A1*C3(K)
      D5=A1*COS(PH)
      D6=A1*SIN(PH)
      M5=K
      DO 29 M=1,M3
      PHM=(M4+M)*PH
      A2=COS(PHM)
      C4(M5)=D4*A2
      C5(M5)=D5*A2
      C6(M5)=D6*SIN(PHM)
      M5=M5+NPHI
```

```
 29 CONTINUE
 11 CONTINUE
    MP=NP-1
    MT=MP-1
    N=MT+MP
    N2N=MT*N
    N2=N*N
    U1=(0.,.5)
    U2=(0.,2.)
    JN=-1-N
    DO 15 JQ=1,MP
    KQ=2
    IF(JQ.EQ.1) KQ=1
    IF(JQ.EQ.MP) KQ=3
    R1=RS(JQ)
    Z1=ZS(JQ)
    D1=D(JQ)
    D2=DR(JQ)
    D3=DZ(JQ)
    D4=D2/R1
    D5=DM(JQ)
    SV=D2/D1
    CV=D3/D1
    T6=CT*D1
    T62=T6+D1
    T62=T62*T62
    R6=CP*R1
    R62=R6*R6
    DO 12 L=1,NT
    R2(L)=R1+D2*XT(L)
    Z2(L)=Z1+D3*XT(L)
 12 CONTINUE
    U3=D2*U1
    U4=D3*U1
    DO 16 IP=1,MP
    R3=RS(IP)
    Z3=ZS(IP)
    R4=R1-R3
    Z4=Z1-Z3
    FM=R4*SV+Z4*CV
    PHM=ABS(FM)
    PH=ABS(R4*CV-Z4*SV)
    D6=PH
    IF(PHM.LE.D1) GO TO 26
    D6=PHM-D1
    D6=SQRT(D6*D6+PH*PH)
 26 IF(IP.EQ.JQ) GO TO 27
    KP=1
    IF(T6.GT.D6) KP=2
    IF(R6.GT.D6) KP=3
    GO TO 28
 27 KP=4
```

```
28 GO TO (41,42,41,42),KP
42 DO 40 L=1,NT
   D7=R2(L)-R3
   D8=Z2(L)-Z3
   Z7(L)=D7*D7+D8*D8
   R7(L)=R3*R2(L)
   Z8(L)=.25*Z7(L)
   R8(L)=.25*R7(L)
40 CONTINUE
   Z4=R4*R4+Z4*Z4
   R4=R3*R1
   R5=.5*R3*SV
   DO 33 K=1,NPHI
   A1=C3(K)
   RR=Z4+R4*A1
   UA=0.
   UB=0.
   IF(RR.LT.T62) GO TO 34
   DO 35 L=1,NT
   R=SQRT(Z7(L)+R7(L)*A1)
   SN=-SIN(R)
   CS=COS(R)
   UC=AT(L)/R*CMPLX(CS,SN)
   UA=UA+UC
   UB=XT(L)*UC+UB
35 CONTINUE
   GO TO 36
34 DO 37 L=1,NT
   R=SQRT(Z8(L)+R8(L)*A1)
   SN=-SIN(R)
   CS=COS(R)
   UC=AT(L)/R*SN*CMPLX(-SN,CS)
   UA=UA+UC
   UB=XT(L)*UC+UB
37 CONTINUE
   A2=FM+R5*A1
   D9=RR-A2*A2
   R=ABS(A2)
   D7=R-D1
   D8=R+D1
   D6=SQRT(D8*D8+D9)
   R=SQRT(D7*D7+D9)
   IF(D7.GE.0.) GO TO 38
   A1=ALOG((D8+D6)*(-D7+R)/D9)/D1
   GO TO 39
38 A1=ALOG((D8+D6)/(D7+R))/D1
39 UA=A1+UA
   UB=A2*(4./(D6+R)-A1)/D1+UB
36 GA(K)=UA
   GB(K)=UB
33 CONTINUE
   K1=0
```

```
      DO 45 M=1,M3
      H4A=0.
      H5A=0.
      H6A=0.
      H4B=0.
      H5B=0.
      H6B=0.
      DO 46 K=1,NPHI
      K1=K1+1
      D6=C4(K1)
      D7=C5(K1)
      D8=C6(K1)
      UA=GA(K)
      UB=GB(K)
      H4A=D6*UA+H4A
      H5A=D7*UA+H5A
      H6A=D8*UA+H6A
      H4B=D6*UB+H4B
      H5B=D7*UB+H5B
      H6B=D8*UB+H6B
   46 CONTINUE
      G4A(M)=H4A
      G5A(M)=H5A
      G6A(M)=H6A
      G4B(M)=H4B
      G5B(M)=H5B
      G6B(M)=H6B
   45 CONTINUE
      IF(KP.NE.4) GO TO 47
      A2=D1/(PI2*R1)
      D6=2./D1
      D8=0.
      DO 63 K=1,NPHI
      A1=R4*C2(K)
      R=R4*C3(K)
      IF(R.LT.T62) GO TO 64
      D7=0.
      DO 65 L=1,NT
      D7=D7+AT(L)/SQRT(Z7(L)+A1)
   65 CONTINUE
      GO TO 66
   64 A1=A2/(X(K)+1.)
      D7=D6*ALOG(A1+SQRT(1.+A1*A1))
   66 D8=D8+A(K)*D7
   63 CONTINUE
      A1=.5*A2
      A2=1./A1
      D8=-PI2*D8+2./R1*(BLOG(A2)+A2*BLOG(A1))
      DO 67 M=1,M3
      G5A(M)=D8+G5A(M)
   67 CONTINUE
      GO TO 47
```

```
41 DO 25 M=1,M3
   G4A(M)=0.
   G5A(M)=0.
   G6A(M)=0.
   G4B(M)=0.
   G5B(M)=0.
   G6B(M)=0.
25 CONTINUE
   DO 13 L=1,NT
   A1=R2(L)
   R4=A1-R3
   Z4=Z2(L)-Z3
   Z4=R4*R4+Z4*Z4
   R4=R3*A1
   DO 17 K=1,NPHI
   R=SQRT(Z4+R4*C3(K))
   SN=-SIN(R)
   CS=COS(R)
   GA(K)=CMPLX(CS,SN)/R
17 CONTINUE
   D6=0.
   IF(R62.LE.Z4) GO TO 51
   DO 62 K=1,NPHI
   D6=D6+A(K)/SQRT(Z4+R4*C2(K))
62 CONTINUE
   Z4=3.141593/SQRT(Z4/R4)
   D6=-PI2*D6+ALOG(Z4+SQRT(1.+Z4*Z4))/SQRT(R4)
51 A1=AT(L)
   A2=XT(L)*A1
   K1=0
   DO 30 M=1,M3
   U5=0.
   U6=0.
   U7=0.
   DO 32 K=1,NPHI
   UA=GA(K)
   K1=K1+1
   U5=C4(K1)*UA+U5
   U6=C5(K1)*UA+U6
   U7=C6(K1)*UA+U7
32 CONTINUE
   U6=D6+U6
   G4A(M)=A1*U5+G4A(M)
   G5A(M)=A1*U6+G5A(M)
   G6A(M)=A1*U7+G6A(M)
   G4B(M)=A2*U5+G4B(M)
   G5B(M)=A2*U6+G5B(M)
   G6B(M)=A2*U7+G6B(M)
30 CONTINUE
13 CONTINUE
47 A1=DR(IP)
   UA=A1*U3
```

```
      UB=DZ(IP)*U4
      A2=D(IP)
      D6=-A2*D2
      D7=D1*A1
      D8=D1*A2
      JM=JN
      DO 31 M=1,M3
      FM=M4+M
      A1=FM*DM(IP)
      H5A=G5A(M)
      H5B=G5B(M)
      H4A=G4A(M)+H5A
      H4B=G4B(M)+H5B
      H6A=G6A(M)
      H6B=G6B(M)
      U7=UA*H5A+UB*H4A
      U8=UA*H5B+UB*H4B
      U5=U7-U8
      U6=U7+U8
      U7=-U1*H4A
      U8=D6*H6A
      U9=D6*H6B-A1*H4A
      UC=D7*(H6A+D4*H6B)
      UD=FM*D5*H4A
      K1=IP+JM
      K2=K1+1
      K3=K1+N
      K4=K2+N
      K5=K2+MT
      K6=K4+MT
      K7=K3+N2N
      K8=K4+N2N
      GO TO (18,20,19),KQ
   18 Z(K6)=U8+U9
      IF(IP.EQ.1) GO TO 21
      Z(K3)=Z(K3)+U6-U7
      Z(K7)=Z(K7)+UC-UD
      IF(IP.EQ.MP) GO TO 22
   21 Z(K4)=U6+U7
      Z(K8)=UC+UD
      GO TO 22
   19 Z(K5)=Z(K5)+U8-U9
      IF(IP.EQ.1) GO TO 23
      Z(K1)=Z(K1)+U5+U7
      Z(K7)=Z(K7)+UC-UD
      IF(IP.EQ.MP) GO TO 22
   23 Z(K2)=Z(K2)+U5-U7
      Z(K8)=UC+UD
      GO TO 22
   20 Z(K5)=Z(K5)+U8-U9
      Z(K6)=U8+U9
      IF(IP.EQ.1) GO TO 24
```

```
      Z(K1)=Z(K1)+U5+U7
      Z(K3)=Z(K3)+U6-U7
      Z(K7)=Z(K7)+UC-UD
      IF(IP.EQ.MP) GO TO 22
   24 Z(K2)=Z(K2)+U5-U7
      Z(K4)=U6+U7
      Z(K8)=UC+UD
   22 Z(K8+MT)=U2*(D8*(H5A+D4*H5B)-A1*UD)
      JM=JM+N2
   31 CONTINUE
   16 CONTINUE
      JN=JN+N
   15 CONTINUE
C
C THREE MULTIPLE BODIES USING THE SIMPLIFIED APPROACH
C NULL OUT ROWS AND COLS FOR THE FIRST DUMMY SEGMENT
C
      DO 100 LSS=1,N
      LS=LSS-1
      Z(LS*N+NP0)=(0.,0.)
      Z(LS*N+NP0-1)=(0.,0.)
  100 Z(LS*N+NP0+MT)=(0.,0.)
      DO 101 LS=1,N
      Z((NP0-2)*N+LS)=(0.,0.)
      Z((NP0-1)*N+LS)=(0.,0.)
  101 Z((NP0-1+MT)*N+LS)=(0.,0.)
      Z((NP0-2)*N+NP0-1)=(1.,0.)
      Z((NP0-1)*N+NP0)=(1.,0.)
      Z((MT+NP0-1)*N+NP0+MT)=(1.,0.)
C
C NULL OUT ROWS AND COLS FOR THE SECOND DUMMY SEGMENT
C
      DO 200 LSS=1,N
      LS=LSS-1
      Z(LS*N+NRF)=(0.,0.)
      Z(LS*N+NRF-1)=(0.,0.)
  200 Z(LS*N+NRF+MT)=(0.,0.)
      DO 201 LS=1,N
      Z((NRF-2)*N+LS)=(0.,0.)
      Z((NRF-1)*N+LS)=(0.,0.)
  201 Z((NRF-1+MT)*N+LS)=(0.,0.)
      Z((NRF-2)*N+NRF-1)=(1.,0.)
      Z((NRF-1)*N+NRF)=(1.,0.)
      Z((MT+NRF-1)*N+NRF+MT)=(1.,0.)
  999 RETURN
      END
      SUBROUTINE ZASMB0(NP1,NP2,MODES,Z,ZWW)
C
C ASSEMBLES MODE INDEPENDENT BLOCKS OF Z
C
      COMPLEX Z(500000),ZWW(10000)
      MT1=NP1-2
```

```
      MP1=NP1-1
      N=MT1+MP1
      MT2=NP2-2
      NBLOCK=2*MODES+1
      NS=NBLOCK*N
      NR=NS+MT2
      NS2=NS*NR
      NWW=NS2+NS
      DO 10 IC=1,MT2
      IC1=IC-1
      DO 10 IR=1,MT2
      K=NWW+IC1*NR+IR
      IW=IC1*MT2+IR
10    Z(K)=ZWW(IW)
      RETURN
      END
      SUBROUTINE ZASMBN(NP1,NP2,MODES,NM,Z,ZSS,ZSW)
C
C ASSEMBLES MODE DEPENDENT BLOCKS IN Z. MODES=TL # OF MODES;
C NM IS THE MODE # OF THE BLOCKS ZSS,ZSW,ZSJ. (IF NM<0 THEN
C ZSS IS OMITTED - ONLY FILLED FOR POSITIVE NM)
C
      COMPLEX ZSS(50000),Z(500000),ZSW(50000)
      MT1=NP1-2
      MP1=NP1-1
      MT2=NP2-2
      N=MP1+MT1
      NBLOCK=2*MODES+1
      NS=NBLOCK*N
      NR=NS+MT2
      MT=MT1+MT2
      MTN=MT*N
      IF(NM.LT.0) GO TO 225
C
C ZSS BLOCKS FOR MODE NM (+ AND - FILLED IN 1 LOOP)
C
      NTOP1=MODES-NM
      NTOP2=NBLOCK-(NTOP1+1)
      NSS2=NTOP1*(N+NR*N)
      NSS1=NTOP2*(N+NR*N)
      DO 200 IC=1,MP1
      IC1=IC-1
      DO 200 IR=1,MP1
      IF(IC.GT.MT1) GO TO 100
      IF(IR.GT.MT1) GO TO 50
      I0=IC1*N+IR
      ITT=IC1*NR+IR
      Z(ITT+NSS1)=ZSS(I0)
      IF(NM.NE.0) Z(ITT+NSS2)=ZSS(I0)
50    I0=MT1+IC1*N+IR
      IPT=IC1*NR+MT1+IR
      Z(IPT+NSS1)= ZSS(I0)
```

```
      IF(NM.NE.0) Z(IPT+NSS2)=-ZSS(I0)
100   IF(IR.GT.MT1) GO TO 150
      I0=N*MT1+IC1*N+IR
      ITP=MT1*NR+IC1*NR+IR
      Z(ITP+NSS1)= ZSS(I0)
      IF(NM.NE.0) Z(ITP+NSS2)=-ZSS(I0)
150   I0=N*MT1+MT1+IC1*N+IR
      IPP=IC1*NR+MT1+MT1*NR+IR
      Z(IPP+NSS1)=ZSS(I0)
      IF(NM.NE.0) Z(IPP+NSS2)=ZSS(I0)
200   CONTINUE
225   CONTINUE
C
C ZSW AND ZWS BLOCKS
C
      NTOP1=MODES+NM
      NTOP2=NBLOCK-(NTOP1+1)
      NSW=NTOP1*N+NS*NR
      NWS=NTOP2*NR*N+NS
      DO 250 IC=1,MT2
      IC1=IC-1
      DO 250 IR=1,N
      ISW=IR+IC1*NR+NSW
      IWS=(IR-1)*NR+IC+NWS
      I0=IC1*N+IR
      Z(ISW)=ZSW(I0)
      Z(IWS)=ZSW(I0)
250   CONTINUE
      RETURN
      END
      SUBROUTINE ZMATSW(NWIRES,NW1,NW2,NP11,NP12,NP13,
     * XH,YH,RH,ZH,NT,XT,AT,NG,XG,AG,MODE,A,Z)
C
c >>>>>>>>>>> revised version <<<<<<<<<<
C
C CALCULATION OF THE SURFACE-WIRE MATRIX ELEMENTS. ATTACHMENT
C POINT NOT AT A SURFACE EDGE, BUT CAN BE ON Z AXIS (IC#1). SURFACE
C START INDEX IS 1.  TWO BORS OF LENGTHS NP11, NP12 AND NP13. WIRE
C START AND STOP POINTS ARE NW1 AND NW2.
C
      COMPLEX CEXP,EXP,Z(50000),G5,G6,G7,CONH,F5,F6,F7
      COMPLEX U,U0,PSI,T0,T1,T2,T3,ST1,ST2,ST3,CON,SP1,SP2,SP3
      COMPLEX U5,U6,U7,U8,U9,CMPLX,T4,T5,T6,T7
      DIMENSION RS1(400),RH(400),ZH(400),XG(400),AG(400),XT(4)
      DIMENSION ZS1(400),D1(400),D(400),S(400),C(400),RS(400)
      DIMENSION ZS(400),S1(400),C1(400),NW1(4),NW2(4),NS(4),AT(4)
      DIMENSION XH(400),YH(400),XS1(400),YS1(400),CU(400),SU(400)
      PI=3.14159
      PI2=2.*PI
      NP1=NP11+NP12+NP13
      NRF=NP11+NP12
      DO 1 L=1,NWIRES
```

```
    1 NS(L)=NW2(L)-NW1(L)+1
      U0=(0.,0.)
      U=(0.,1.)
C
C DEFINE SURFACE GEOMETRY TERMS
C
      MP=NP1-1
      MT=MP-1
      NROW=MP+MT
      DO 5 I=2,NP1
      I2=I-1
      RS(I2)=.5*(RH(I)+RH(I2))
      ZS(I2)=.5*(ZH(I)+ZH(I2))
      DR=RH(I)-RH(I2)
      DZ=ZH(I)-ZH(I2)
      D(I2)=SQRT(DR**2+DZ**2)
      S(I2)=DR/D(I2)
    5 C(I2)=DZ/D(I2)
C
C DEFINE WIRE GEOMETRY TERMS
C
      NW=NW2(NWIRES)-NW1(1)
      NWP=NW+1
      MT2=NWP-2
      DO 10 N=2,NWP
      N0=N-1
      I=NP1+N
      I2=I-1
      RS1(N0)=.5*(RH(I)+RH(I2))
      ZS1(N0)=.5*(ZH(I)+ZH(I2))
      XS1(N0)=.5*(XH(I)+XH(I2))
      YS1(N0)=.5*(YH(I)+YH(I2))
      DX=XH(I)-XH(I2)
      DY=YH(I)-YH(I2)
      D1(N0)=SQRT(DX**2+DY**2)
C FOR WIRES PARALLEL TO THE XY PLANE SIN(V)=1 AND COS(V)=0
      S1(N0)=1.
      C1(N0)=0.
      CU(N0)=DX/D1(N0)
      SU(N0)=DY/D1(N0)
   10 CONTINUE
      CON=U/PI2/2.
C INTEGRATING FROM 0 TO 2*PI
      O1=PI
      O2=PI
      JN=-1-NROW
C
C SEGMENT LOOPS: q=WIRE, p=SURFACE
C
      DO 100 JQ=1,NW
      KQ=2
      IF(JQ.EQ.1) KQ=1
```

```
      IF(JQ.EQ.NW) KQ=3
      H1=D1(JQ)/2.
      ZW=ZS1(JQ)
      DO 22 IP=1,MP
      ST1=U0
      ST2=U0
      ST3=U0
      SP1=U0
      SP2=U0
      SP3=U0
      AA=S(IP)*CU(JQ)
      BB=S(IP)*SU(JQ)
      RD=RS(IP)*D1(JQ)
      DD=D(IP)*D1(JQ)
      CONH=CON*D(IP)
C
C FIRST TERM (H-INTEGRATION)
C
      DO 30 I=1,NT
      H=H1*XT(I)
      HHD=2.*H/D1(JQ)
      XW=XS1(JQ)+H*CU(JQ)
      YW=YS1(JQ)+H*SU(JQ)
C
C PHI INTEGRATIONS FOR G-HAT FUNCTIONS
C
      G7=U0
      G5=U0
      G6=U0
      DO 32 K=1,NG
      PH=O1*XG(K)+O2
      PHM=PH*FLOAT(MODE)
      XS=RS(IP)*COS(PH)
      YS=RS(IP)*SIN(PH)
      EXP=CEXP(CMPLX(0.,-PHM))
      RP=SQRT((XS-XW)**2+(YS-YW)**2+(ZS(IP)-ZW)**2)
      PSI=CEXP(CMPLX(0.,-RP))/RP
      F5=EXP*COS(PH)*PSI
      F6=EXP*SIN(PH)*PSI
      F7=EXP*PSI
      G7=G7+F7*AG(K)
      G5=G5+F5*AG(K)
   32 G6=G6+F6*AG(K)
      G7=O1*G7
      G5=O1*G5
      G6=O1*G6
      T0=G5*AA/4.
      T1=T0*HHD
      T2=G6*BB/4.
      T3=T2*HHD
      T4=G5*SU(JQ)/2.
      T5=T4*HHD
```

```
      T6=-G6*CU(JQ)/2.
      T7=T6*HHD
      ST1=ST1+AT(I)*(T0+T2)
      ST2=ST2+AT(I)*(T1+T3)
      ST3=ST3+AT(I)*G7/DD
      SP1=SP1+AT(I)*(T4+T6)
      SP2=SP2+AT(I)*(T5+T7)
      SP3=SP3+AT(I)*U*G7*FLOAT(MODE)/RD
   30 CONTINUE
C
C ZSW-t TERMS (K1,K2,K3,K4)
C
      U5=(ST1-ST2)*CONH*H1
      U6=(ST1+ST2)*CONH*H1
      U7=-ST3*CONH*H1
C
C ZSW-p TERMS (K5,K6)
C
      U8=SP1*CONH*H1
      U9=(SP2+SP3)*CONH*H1
      K1=IP+JN
      K2=K1+1
      K3=K1+NROW
      K4=K2+NROW
      K5=K2+MT
      K6=K4+MT
      GO TO (18,20,19),KQ
   18 Z(K6)=U8+U9
      IF(IP.EQ.1) GO TO 21
      Z(K3)=Z(K3)+U6-U7
      IF(IP.EQ.MP) GO TO 22
   21 Z(K4)=U6+U7
      GO TO 22
   19 Z(K5)=Z(K5)+U8-U9
      IF(IP.EQ.1) GO TO 23
      Z(K1)=Z(K1)+U5+U7
      IF(IP.EQ.MP) GO TO 22
   23 Z(K2)=Z(K2)+U5-U7
      GO TO 22
   20 Z(K5)=Z(K5)+U8-U9
      Z(K6)=U8+U9
      IF(IP.EQ.1) GO TO 24
      Z(K1)=Z(K1)+U5+U7
      Z(K3)=Z(K3)+U6-U7
      IF(IP.EQ.MP) GO TO 22
   24 Z(K2)=Z(K2)+U5-U7
      Z(K4)=U6+U7
   22 CONTINUE
      JN=JN+NROW
  100 CONTINUE
C
C FOR MULTIPLE BORS WRITE OVER DUMMY SEGMENT ROWS
```

```
C WRITE OVER ROWS AND COLS FOR FIRST DUMMY SEG.
C
      DO 101 LSS=1,MT2
      LS=LSS-1
      Z(LS*NROW+NP11)=(0.,0.)
      Z(LS*NROW+NP11-1)=(0.,0.)
  101 Z(LS*NROW+NP11+MT)=(0.,0.)
C
C WRITE OVER ROWS AND COLS FOR SECOND DUMMY SEG.
C
      DO 201 LSS=1,MT2
      LS=LSS-1
      Z(LS*NROW+NRF)=(0.,0.)
      Z(LS*NROW+NRF-1)=(0.,0.)
  201 Z(LS*NROW+NRF+MT)=(0.,0.)
C
C WRITE OVER DUMMY SEGMENTS IN THE CASE OF MULTIPE WIRES
C
      IF(NWIRES.EQ.1) GO TO 292
      NSPTS=0
      DO 291 L=1,NWIRES-1
      NSPTS=NSPTS+NS(L)
      DO 291 I=1,NROW
C
C SET COLS TO ZERO FOR STRIPS
C
      IN=(NSPTS-2)*NROW
      Z(IN+I)=U0
      Z(IN+I+NROW)=U0
  291 CONTINUE
  292 RETURN
      END
      SUBROUTINE ZMATWW(NWIRES,NW1,NW2,XH,YH,RH,ZH,NT,XT,AT,A,Z)
C
C *** MODS FOR DIPOLE -- RECTANGULAR COORDINATES ARE SENT OVER ***
C COMPUTE MATRIX ELEMENTS FOR MULTIPLE WIRES USING GLISSON METHOD
C NWIRES= # OF WIRES; NW1(I),NW2(I) ARE START AND STOP POINTS.
C &&&&& WIRES NEED NOT BE IN THE Z=0 PLANE &&&&&
C
      COMPLEX CEXP,Z(10000),CON,CMPLX
      COMPLEX U,U0,PSI,SUM1,SUM2,SUM3,U5,U6,U7
      DIMENSION RH(400),ZH(400),XT(4),AT(4),XH(400),YH(400)
      DIMENSION D1(400),S1(400),C1(400)
      DIMENSION NW1(4),NW2(4),NS(4),XS1(400),YS1(400),ZS1(400)
      DIMENSION CU(400),SU(400)
      PI=3.141592
      PI2=2.*PI
      PD2=PI/2.
      U0=(0.,0.)
      U=(0.,1.)
C
C DEFINE GEOMETRY TERMS FOR THE WIRE. XH,YH,RH,ZH ARE ALL KNOWNS.
```

```
C
      DO 5 L=1,NWIRES
    5 NS(L)=NW2(L)-NW1(L)+1
      NS1=NW2(NWIRES)-NW1(1)
      NPS=NS1+1
      DO 10 N=2,NPS
      N0=N-1
      I=NW1(1)+N-1
      I2=I-1
      XS1(N0)=.5*(XH(I)+XH(I2))
      YS1(N0)=.5*(YH(I)+YH(I2))
      ZS1(N0)=.5*(ZH(I)+ZH(I2))
      DX=XH(I)-XH(I2)
      DY=YH(I)-YH(I2)
      D1(N0)=SQRT(DX**2+DY**2)
      CU(N0)=DX/D1(N0)
      SU(N0)=DY/D1(N0)
      S1(N0)=1.0
      C1(N0)=0.0
   10 CONTINUE
      NROW=NS1-1
      JN=-1-NROW
      DO 500 JQ=1,NS1
      KQ=2
      IF(JQ.EQ.1) KQ=1
      IF(JQ.EQ.NS1) KQ=3
      Q1=D1(JQ)/2.
      DO 22 IP=1,NS1
      LQ=0
      IF(IP.EQ.JQ) LQ=1
      CON=D1(IP)/4./PI*U
      SUM1=U0
      SUM2=U0
      SUM3=U0
      AA=CU(IP)*CU(JQ)+SU(IP)*SU(JQ)
C
C H INTEGRATION -- SUBTRACT OUT SINGULARITY IF JQ=IP
C AND SAME SEGMENT (N11=N21): DESIGNATED LQ=1
C
      DO 100 I=1,NT
      H=Q1*XT(I)
      IF(LQ.NE.1) GO TO 40
      RP=SQRT(H**2+A*A)
      GO TO 50
   40 XP=XS1(JQ)+H*CU(JQ)*S1(JQ)
      YP=YS1(JQ)+H*SU(JQ)*S1(JQ)
      RP=SQRT((XS1(IP)-XP)**2+(YS1(IP)-YP)**2+(ZS1(JQ)-ZS1(IP))**2)
   50 PSI=CEXP(CMPLX(0.,-RP))
c     IF(LQ.NE.1) GO TO 60
c     PSI=PSI-(1.,0.)
   60 PSI=PSI/RP
      SUM1=SUM1+PSI*AA*AT(I)/4.
```

```
      SUM2=SUM2+PSI*AA*AT(I)/2./D1(JQ)*H
      SUM3=SUM3+PSI*AT(I)/D1(IP)/D1(JQ)
  100 CONTINUE
      X1=0.
      X2=0.
      X3=0.
c     IF(LQ.NE.1) GO TO 200
c     DQ=D1(JQ)/2.
c     SDQ=SQRT(DQ**2+A**2)
c     XI0=ALOG(SDQ+DQ)-ALOG(SDQ-DQ)
c     X1=XI0*AA/4.
c     X3=XI0/D1(IP)/D1(JQ)
c 200 CONTINUE
      SUM1=(SUM1*Q1+X1)*CON
      SUM2=(SUM2*Q1+X2)*CON
      SUM3=(SUM3*Q1+X3)*CON
      U5=SUM1-SUM2
      U6=SUM1+SUM2
      U7=-SUM3
      K1=IP+JN
      K2=K1+1
      K3=K1+NROW
      K4=K2+NROW
      GO TO (18,20,19),KQ
   18 CONTINUE
      IF(IP.EQ.1) GO TO 21
      Z(K3)=Z(K3)+U6-U7
      IF(IP.EQ.NS1) GO TO 22
   21 Z(K4)=U6+U7
      GO TO 22
   19 CONTINUE
      IF(IP.EQ.1) GO TO 23
      Z(K1)=Z(K1)+U5+U7
      IF(IP.EQ.NS1) GO TO 22
   23 Z(K2)=Z(K2)+U5-U7
      GO TO 22
   20 CONTINUE
      IF(IP.EQ.1) GO TO 24
      Z(K1)=Z(K1)+U5+U7
      Z(K3)=Z(K3)+U6-U7
      IF(IP.EQ.NS1) GO TO 22
   24 Z(K2)=Z(K2)+U5-U7
      Z(K4)=U6+U7
   22 CONTINUE
      JN=JN+NROW
  500 CONTINUE
      IF(NWIRES.EQ.1) GO TO 297
      NSPTS=0
      DO 291 L=1,NWIRES-1
      NSPTS=NSPTS+NS(L)
      DO 291 I=1,NROW
C
```

```
C USE THE SIMPLIFIED METHOD OF HANDLING MULTIPLE WIRES
C SET COLS TO ZERO FOR STRIPS
C
      IN=(NSPTS-2)*NROW
      Z(IN+I)=U0
      Z(IN+I+NROW)=U0
C
C SET ROWS TO ZERO FOR STRIPS
C
      IN=NSPTS-2+(I-1)*NROW
      Z(IN+1)=U0
      Z(IN+2)=U0
  291 CONTINUE
C
C SET DIAGONALS TO 1 FOR STRIPS
C
      NSPTS=0
      DO 296 L=1,NWIRES-1
      NSPTS=NSPTS+NS(L)
      I0=NSPTS-2
      I1=I0*NROW+NSPTS-2
      Z(I1+1)=(1.,0.)
      Z(I1+NROW+2)=(1.,0.)
  296 CONTINUE
  297 RETURN
      END
```

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